PRETREATMENT CAPABILITIES AND BENEFITS OF ELECTROCOAGULATION

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CHAPTER 1.

EXECUTIVE SUMMARY

1.0   SUMMARY

The goals of the research project were 1) to demonstrate the removal capabilities of the electrocoagulation (EC) technology and 2) to define the best application of the technology within the context of providing pretreatment to reverse osmosis systems.

EC is the application of electrical potential across electrodes placed in a moving solution to be treated. Above a characteristic voltage dependent on the electrode material, some of the electrode will dissolve (become ionized) in solution.   In this way, and only this way, EC resembles chemical coagulation - in that iron or aluminum ions, for instance, may be introduced into the solution to be treated.   The EC process goes beyond chemical coagulation in that electrical current moves through the solution and promotes several other mechanisms that influence removal of species from solution. This includes the destabilization of colloids and oxidation-reduction reactions to name just two.

Although EC equipment has been available for several years and significant removal capabilities have been reported, only recently have design improvements made cost-effective and larger volume treatment possible. The application of EC as pretreatment to membrane processes has not been reported in the literature and only one example (EC in front of RO at a car wash) has been identified. The research undertaken was of an applied nature using bench-scale equipment of a commercially available technology.

The research focused on testing an EC device on both mock and real waters over a wide range of contaminants to be removed.   The test variables included EC operational parameters as well as solution / water quality variables.   Over 100 separate EC runs were made. Early runs involved a lengthy protocol to characterize and document the treatment and its effects. These runs focused on the removal of suspended solids as this was known to be a cost-effective application of EC. Further, the removal of suspended solids was easily and inexpensively characterized through the measurement of turbidity.   This allowed for rapid indication of test results and thus a time-efficient approach to study system variables and to refine test protocols. Protocols were later refined and simplified as understanding of the importance and interaction of variables developed.

Over the course of the research, the suspended solids studied included:

- Oil/water emulsions
- Humic acid / tannic acid mixtures
- Latex paint
- Hydrocarbon condensate from a coal-cleaning operation

Although there was no attempt to optimize removal levels, removal efficiencies measured in terms of turbidity were consistently over 99 percent over the entire range of operational and test solution variables.

Later experimental runs studied the removal of metals and semi-metals from solutions. The elements (in solution in ion or complex form) included:

- Al, Ag, As, Ba, Ca, Cd, Cr, Cs, Fe, I, Mg, Na, Si, Sr, and Zn.

Other compounds studied included:

- Nitrate
- Phosphate
- Perchlorate
- DDT
- Chlorpyrifos
- Lindane
- Malathion

The level of removal of these ions and compounds varied considerably. Some ions were removed at high levels regardless of the background solution chemical matrix and operating conditions (Ag, Cd, Cr, Zn, for example) while others varied either dependent on background matrix, operation conditions, or both.

Examination of the literature showed instances of high removal of most of the ions and compounds studied. Clearly, the removal of many items depends on the specific removal situation.

Amperage appears to be the key electrical characteristic necessary for removal. In some systems a threshold of amperage was necessary before any significant removal was attained.

The effective of salinity was minor on removal levels but major on the power required to accomplish the removal. The higher conductivity (lower resistance) of higher salinity solutions allowed a given amperage level to be reached at much lower voltage and thus a lower power.

An emerging trend in membrane technology applications is the use of low-pressure membranes (ultrafiltration and microfiltration) as pretreatment to reverse osmosis units. The low pressure membranes provide a barrier that offers better and more general protection of the reverse osmosis membrane than conventional pretreatment schemes. The low pressure membranes, however, are still susceptible to their own fouling and performance reduction – particularly for treatment of high suspended solids feeds and especially where these feeds have an organic nature.

Due to the excellent EC removal of suspended solids and the simplicity of the EC operation the most promising application of EC in a membrane system was found to be as pretreatment to a multi-membrane system of UF / RO or MF / RO. In this function the EC provides protection of

the low-pressure membrane that is more general than that provided by chemical coagulation and more effective.   EC is more effective at removing species that chemical coagulation and other alternatives can remove and it removes many species that chemical coagulation cannot remove.

To explore this application, several small stirred cell membrane tests were conducted to demonstrate the susceptibility of UF membranes to fouling and the effect of EC treatment to minimize the fouling.

In sum, the project research demonstrated several of removal capabilities of the EC system, provided an understanding of the relative importance of the operational variables, and provided the basis for recommending the application of EC as pretreatment to the multi-membrane systems of UF / RO or MF / RO.

CHAPTER 2.

BACKGROUND AND LITERATURE SURVEY

2.1   BACKGROUND FOR ELECTROCOAGULATION TECHNOLOGY

Electrocoagulation (EC) processes are a non-chemical, electrical means of removing suspended solids, colloidal material, and sparingly soluble salts as well as other dissolved solids from waters and wastewaters. EC has been successful in removing pesticides, radionuclides and is effective in removing bacteria, viruses, and biohazards, etc. Most systems use DC current where electrode plates are sacrificed (dissolved into solution) causing increased high metal concentrations that end up as oxide precipitates.   Due to improved process design and equipment materials this electrical technology now offers advantages over chemical processes.

The removal capabilities of EC are thought to be due to several different treatment effects that include:

1.   Seeding, resulting from the anode reduction of metal ions to metal that become new centers for larger, stable, insoluble complexes that precipitate as complex metal oxides.
2.   Emulsion breaking resulting from the oxygen and hydrogen ions that bond into the water receptor sites of oil molecules, creating a water insoluble separation of water from oil, drillers, mud, dye inks, etc.
3.   Halogen complexing as the metal ions bind themselves to the chlorine atom in a chlorinated hydrocarbon, resulting in a large insoluble complex; this permits separation of pesticides, herbicides, chlorinated hydrocarbons, etc., from water.
4.   Bleaching by the oxygen ions produced in the reaction chamber, leading to oxidation of dyes, cyanides, bacteria, viruses, biohazards, etc.
5.   Electron flooding of the water eliminates the polar/bipolar effect of the water complex, allowing colloidal materials to precipitate; plus the increase of electrons creates an osmotic pressure that ruptures bacteria, cysts, and viruses.
6.   Oxidation/reduction reactions are forced to their natural endpoint within the reaction chamber, which speeds up the natural process that occurs in wet chemistry.

2.1.1   Applications

EC has been successfully used for (1, 2, 3, 4, 5):

- Removing metals and oils from wastewater
- Recycling wastewater for reuse in the same environment
- Reconditioning antifreeze by removing oils, metals, and dirt
- Pre-treating by removing silica, hardness, TSS, and some TDS
- Removing bacteria and chlorine before discharge
- Pre-treating drinking water
- Removing heavy metals

Specific applications include:

Textile and dye industry	Cooling towers
Groundwater remediation	Water reuse
Process rinse and wastewater	Metal recovery
Potable water	Influent/effluent water control
Industrial wastewater	Pre-treatment for drinking water
Oil emulsion breaking	Medical waste remediation
Antifreeze recycling	Removal of non-ionic colloids
Landfill runoff	

2.1.2   Comparison with Chemical Coagulation

In this section capabilities are contrasted with those from chemical precipitation. Chemical coagulation chemicals end up in the sludge, increase its volume, and make the sludge more difficult to dewater. They also may increase the TDS content of the recovered liquid. EC can reduce concentrations below that possible with chemical precipitation, and can eliminate the use of expensive chemical agents. EC produces a cleaner water than either chemical precipitation or sedimentation (6).

The following table provides a comparison of removal percentages:

	Electrocoagulation	**Chemical Coagulation**	**Sedimentation**
TSS	95 to 99%	80 to 90%	50 to 70%
BOD	50 to 98%	50 to 80%	25 to 40%
Bacteria	95 to 99.999%	80 to 90%	25 to 75%

The EC floc tends to contain less bound water, is more shear resistant, and is readily filterable. Perhaps most important, electrocoagulation can precipitate out large quantities of different contaminants in one operation.

Specific removal capabilities for EC found in the literature (1, 2, 3, 4, 5, 6) include:

Removal Focus	**% Removal**
BOD	90%+
TSS (clay, silt, coal, etc.)	99%+
Fats, oils and grease in water	93 to 99%+
Water in sludge	50 to 80%+
Heavy metal	95 to 99%+
Phosphate	93%+
Bacteria, viruses, cysts	99.99%+
TDS	15 to 30%+

EC produces an environmentally friendly sludge in the 6 to 7 pH range. Metals in the sludge at this pH range are stabilized in a non-hazardous form as oxides, and they pass the EPA TCLP and California Title 22 STLC and TTLC leach tests. Chemically produced sludge, on the other hand, is usually in the caustic pH range with metals in the form of hydroxides. In this form the metals can become soluble again at the neutral pH range of around 7. In addition, the volume of chemical sludge is much greater due to the presence of most of the added chemicals.

2.1.3 Summary of Benefits (relative to chemical coagulation)

- EC requires no chemicals
- EC requires no toxic chemical safety requirements
- EC kills virus and cysts as well as coliform bacteria
- EC provides better removal capabilities for the same species that chemical coagulation can remove
- EC removes many species that chemical coagulation cannot remove
- EC produces a cleaner water
- EC produces less sludge
- EC sludge is more readily filterable.
- EC sludge contains metal oxides that pass the leachability tests
- EC sludge may be utilized as a soil additive
- EC sludge disposal costs are lower (lower volume, and non-hazardous nature of the sludge)
- EC has minimal setup time; turn on the switch
- EC has no temperature effect; will operate over a wide range of temperature
- EC has no moving parts
- EC has small space requirement; a 1 MGD (3785 m3/d) system would occupy less than 500 square feet (46.5 m2).

2.1.4 Other Comments

EC will not remove low molecular weight organics, sodium, potassium, chloride and other monovalent ions. It will remove pesticides and radionuclides (such as from the use of warheads using depleted uranium).

2.1.5 Costs

Over a wide range of applications, capital costs typically range from $1 to 3/gpd (0.26 to 0.79 lpd) while operating costs are from $0.10 to 1.50 per 1000 gallons or $0.03 to 0.40/m3 (1, 2, 3, 5). These costs do not reflect several of the benefits mentioned above.

2.1.6 Treatment Example

In the Venezuelan floods of a few years ago both U.S. and German military brought in membrane system to help produce water. These systems operated for only short periods of time (less than one hour) before the cartridge filters became clogged with silt and silica and other suspended solids. In contrast, an electrocoagulation system operated continuously for 30 days without problems (7)

2.1.7 Fit with Existing and New Military Treatment Systems

Current military portable desalination and water purification systems employ a variety of pretreatment options depending mainly on the size of the equipment. Smaller systems may use only a 50 micro self-cleaning filter followed by a 5 micron filter cartridge. Cyclone separators are used on some systems for heavier dirt and sand removal. Larger systems employ a chemical coagulant system followed by a media filter.

These systems have limited success with highly turbid waters.

New treatment units will be more effective in high turbidity waters through the use of low-pressure membranes as pretreatment to the RO. The TWPS 1,500 gph (5,780 lph) system will use microfiltration (MF) as pretreatment to RO. No coagulation is recommended for this system. The small LWP system (75 gph or 284 lph) can use a coagulation system. A larger demonstration unit (100,000 gpd or 379 m3/d) will employ coagulation followed by ultrafiltration (UF) and then the RO (8).

The principal investigator is also aware of commercial pretreatment systems designed specifically for the use with the military systems – such as the multifunctional modular fluid filtration systems (MMFFS) made by TECWAR. These systems do not take advantage of the benefits of electrocoagulation.

The potential fit of EC within the new treatment unit concept is to provide a simpler, more effective pretreatment. The benefits should be most apparent in systems that would employ chemical coagulation – with or without a following low-pressure membrane prior to the RO system. In a UF/RO system without chemical coagulation, use of EC has potential to reduce the cleaning frequency of the UF and RO membranes (including the backwash frequency of the UF system), increase the flux of both UF and RO systems, and result in better removal efficiencies for those species that either UF or UF and RO can remove.

2.1.8 Fit with Municipal Treatment Systems

Many of the newer municipal desalination systems are turning to low-pressure membranes as the pretreatment to the RO system. This includes, for instance, the largest inland municipal desalting facility planned for Thornton, Colorado. It will consist of 50 MGD (189,250 m3/d) MF and 15 MGD (56,800 m3/d) RO.

2.1.9 Powell Water Systems EC Technology

There were several reasons to work with the Power Water Systems' EC technology. First, conventional EC technologies are limited in the size of a single stand-alone processing unit. Most systems are limited to perhaps 20 gpm (76 lpm) by design constraints. The Powell systems, however can be designed up to over 2 MGD (7,750 m3/d) per unit. Second, the Powell systems contain simple plate electrodes and blades that are inexpensive and simple to install and remove. This is unlike most other designs that feature machined and even laser-

drilled electrodes.   Third, the energy use has been decreased to 3% of that of many conventional designs. This results from the use of separate, simple, flat, multiple blades with power attached to only a few of the blades.   Powell Water Systems has several patents on their unique designs. Finally, Scott Powell of Powell Water Systems was able to provide convincing evidence of his knowledge and experience and thus his ability to be a strong asset to the project.

CHAPTER 3.

RESEARCH OBJECTIVES, TECHNICAL APPROACH AND METHODOLOGY

3.1   RESEARCH OBJECTIVES

The goals of the research project were 1) to demonstrate the removal capabilities of the electrocoagulation (EC) technology and 2) to define the best application of the technology within the context of providing pretreatment to reverse osmosis systems.

The specific research objectives were:

- To define the pretreatment performance capabilities of electrocoagulation
- To determine the effect of electrocoagulation pretreatment on RO performance
- To develop preliminary level cost estimates of EC pretreatment
- To determine preferred processing conditions for a range of water qualities
- To determine the advantages and benefits of electrocoagulation pretreatment

In meeting these objectives several questions were addressed:

- What are the EC performance (removal) capabilities?
- How does EC performance change with salinity and varying water quality parameters?
- How does operating cost vary with salinity and varying water quality parameters?
- In what treatment situations will EC offer the most benefits?

3.2   TECHNICAL APPROACH AND METHODOLOGY

While the background section described the general capabilities of EC, there has never been a comprehensive study of the performance capabilities over a wide range of water quality parameters and salinities.   Most studies have focused on a narrow application of the technology to solve a particular industrial problem.   Likewise there has never been a study addressing the effect of EC treatment on membrane performance.

Thus the research focused on defining and demonstrating the removal capabilities of the EC technology over a range of salinities and water quality parameters AND demonstrating the effect of using EC as a pretreatment step on membrane performance.

The project tasks were laboratory oriented with the exception of a study of the electrocoagulation literature.

Two types of laboratory tests were undertaken to meet the project objectives. The first involved the electrocoagulation removal of contaminants from solution.   These studies helped to define the removal capabilities of the EC system as a function of EC operating variables and contaminant solution variables. The second type of laboratory tests involved membrane studies

using a simple dead-end flow cell. These studies helped to define the effect of EC on membrane system flux.

3.2.1   Bench-scale EC Test Unit

Due to the many varying parameters and number of tests that were conducted, it was both convenient and necessary to use a small bench-scale EC system.   The tests used a 1.0 lpm EC unit manufactured by Powell Water Systems.   The test unit is pictured below.

9 blades (electrodes) with power sent to blades 1 & 9

overflow collection area

EC reaction chamber

drain to Collection container
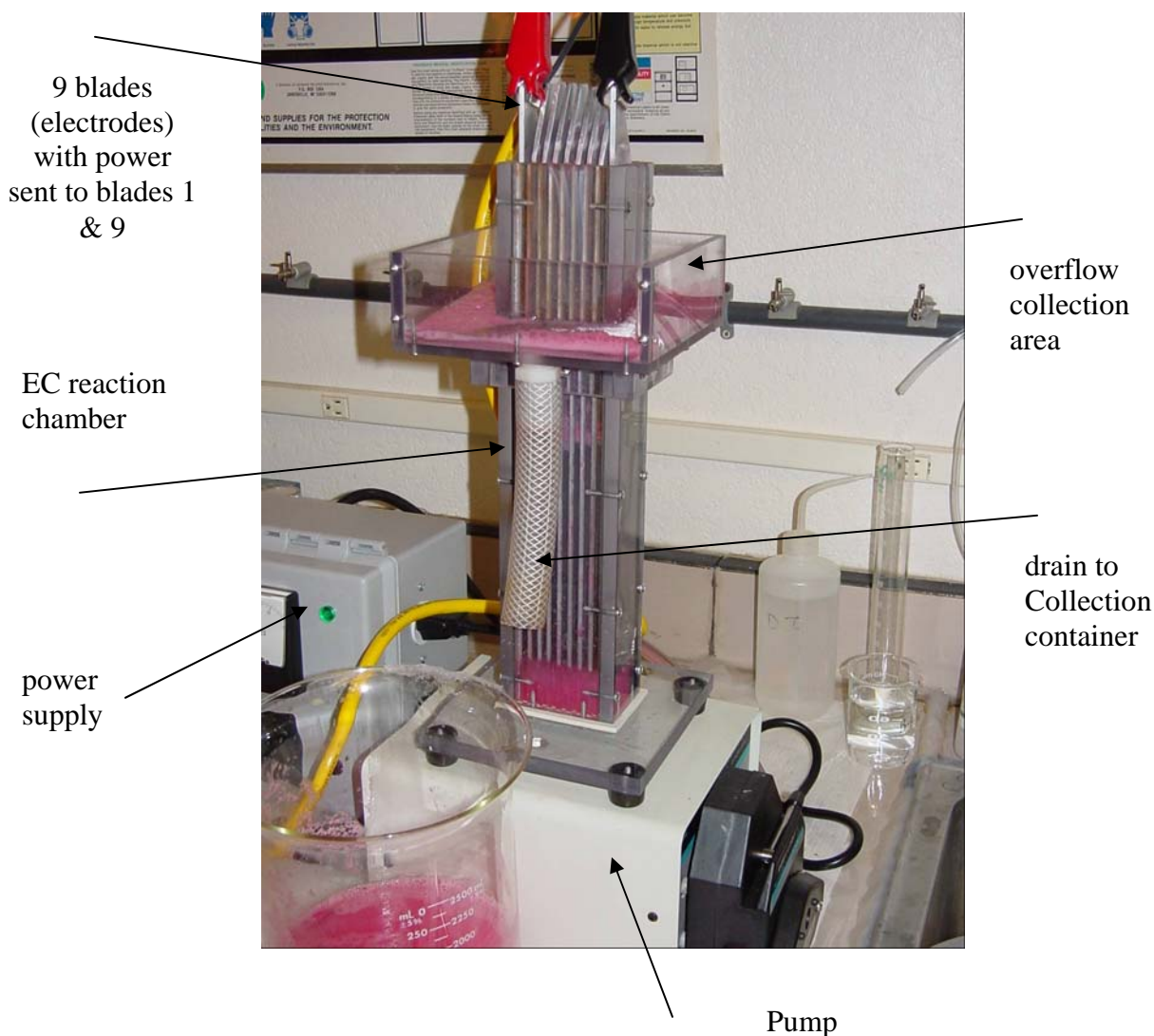
power supply

Pump

The Power Water System's 110V bench-scale demonstration EC unit consists of power supply, peristaltic pump, reaction chamber, metal blades sets (iron and aluminum), and supplies.

AC power was transformed to DC power and transmitted from the power supply to the EC electrodes (blades) by cable.   Most typically power was connected to the 2 outer blades as shown in the picture.   Alternatives to this are discussed below in the power section. At the start of a test run, test solution is pumped into the bottom of the reaction chamber prior to sending

power to the blades. Pump and power are then turned on to initiate the run. Because the initial chamber solution volume does not see power during its entire residence time, it is collected separately and discarded as being unrepresentative of the fully treated solution. During the run test solution flows through the reaction chamber moving up between the blades before spilling over the top into a holding area before draining to a collection container.   The pump and power are turned off prior to treatment of the entire feed solution.

Most tests involve small volumes of feed solution (less than one gallon) run for less than 5 minutes in a once through mode.

3.2.2   General Testing Sequence
The straightforward testing sequence involved:

- Preparation of feed solutions
- Processing the feed solutions using the bench scale EC unit
    - Making a series of runs varying operational parameters such as pH, electrode material (iron or aluminum), and voltage across the electrodes.
- Collecting processed water samples
- Analyzing the treated solution for selected parameters
- Gravity filtering collected samples using standard 11 micron filter paper to separate solids from liquid.
- Analyzing the filtrate for selected parameters.
- Comparing feed and filtrate concentrations to determine removal levels and changes of selected parameters.

The more detailed protocol used for making the EC runs is given in a later section.

3.2.3   Solutions and Contaminants

3.2.3.1 Test waters: Most of the tests used mock waters (synthetic waters) made from dry chemicals added to DI water. A computer program developed in a previous contract (9) was used for determining what and what amounts of individual salts to use to make up a desired solution.   Protocols were available from this work to dictate what order and under what conditions (pH, temperature, etc.) each salt is to be added to the solution to ensure dissolution and avoid precipitation that might otherwise occur.

3.2.3.2 Categories of Contaminants: Early in the project a list of possible contaminants was divided into five categories that differed in terms of:
- whether they compromised membrane performance or not
- what type of analysis would be required to document their concentrations

The 5 groups were:

Group I
- contaminants that foul membranes in their present form
- contaminants for which turbidity can be used as an indication of removal success

- examples include: oil/water emulsions, silt, humic / tannic acid, others

Group II
- Contaminants the foul membranes when concentrated sufficiently
- Contaminants for which turbidity cannot be used as an indicator of removal success
- Examples include: silica, calcium carbonate

Groups III
- Contaminants that do not, in general, foul membranes
- Inorganic contaminants
- Examples include: arsenic, heavy metals

Group IV
- Same as Group III but organic in nature
- Examples include: pesticides, chemical agents

Group V
- Same as Group III but biological in nature
- Examples include: biological agents

The difficulty in testing contaminants increases with increasing group number.   Contaminant sample costs, handling challenges, and analytical costs all increase significantly.

Choice of priority contaminants and test levels were guided by input from the project managers, recommended challenge species levels from the U.S. Army Center for Health Promotion and Preventive Medicine (for the 1500 TWPS membrane system), and discussions with this later group on surrogates that might be used for testing of various contaminants (radionuclides, biological agents, and non-agent chemicals).

3.2.3.3 Tests with Contaminants: The testing approach was to begin with studying the removal of suspended solids / particulates; the items of Group I.   The solutions were easy to prepare and the removal results were easily and quickly followed by measuring the turbidity of solutions. This approach provided a convenient means of studying the effect of many EC system and solution variables on EC removal performance.

Another reason for working with Group I contaminants was that they are known to compromise membrane performance through fouling / plugging the membrane surface.   Consequently their effect on membrane performance was expected to be easily demonstrated.

Following gaining of a basic understanding of how the EC system operating parameters affect removal performance through the study of Group I contaminants, the testing approach was to would move on to the study of Group II contaminants.   This was to be followed in turn by study of Group III, IV, and V contaminants.   Due to the above-mentioned challenges that increase with group number, most testing was done on contaminants from Groups I through III.   Some limited testing was done of Group IV contaminants and none of Group V.

3.2.3.4 Test Solutions: The exact nature of the base solutions used in the mocks is given in Table 4.2 of Chapter 4. Most runs were made with a 'standard' base solution designated as base solution #8. It was representative of a ground water sample with hardness present and a total TDS of about 1000 mg/L. It was comprised of the major ions Na, Cl, Ca, SO4, K, Mg, and HCO3.

Most of the runs processed were mock solutions of contaminants present against the base solution background. The solutions were prepared using software previously developed to designate the amount of different salts needed to makeup a water of given ionic composition. The base solutions were simple to make up requiring only a weighing scale and a magnetic stirrer and stirrer bar to aid in mixing of the added salts.

The greater challenge was in dealing with the added contaminants that were the focus of the EC removal studies. Contaminants having an organic nature (oil-water emulsions, tannic and humic acids) tended to adhere to the container walls and thus change in composition with time. These solutions had to be well stirred before use and were characterized just before use.

Silt samples provided a challenge in that the range of particulate size was large. Samples were filtered using 11 micron paper filters (Whatman No. 1) prior to use. This removed larger particulates that would tend to settle quickly.

One series of runs involved 12 metal salts (a metal soup) added to the base solution. The initial target was to get each metal ion in the feed solution at roughly 10 mg/L. The mother solution of all salts quickly formed precipitates. Prior to the EC runs the solution was filtered using the 11 micron paper filter to remove visible precipitates. The resulting metal ion levels ranged from 0.3 mg/L to 11 mg/L.

3.2.3.5 Tests Conducted on Real Waters: Four real waters were identified and eventually studied. These waters were:

- Industrial wastewater containing high levels of arsenic and silica
- Cooling tower water containing high levels of silica
- Hydrocarbon condensate from a coal-cleaning operation containing high levels of small carbon particulates

3.2.4 EC System Variables

3.2.4.1 Electrode Blades: Three different blade materials were used in the studies: aluminum, iron, and magnesium. Iron blades were used for over 90% of all runs. They are used in most EC systems and were chosen as the standard blade for the studies. The blades are 32 mm thick and approximately 3.2 cm wide and 36 cm in length. One corner is cut off one end of the blades to facilitate electrode attachment.

3.2.4.2 Power: The power supply for the EC unit is manufactured by Payne Engineering. The unit converts AC power to DC power and regulates the output voltage by turning the AC signal on and off according to a dialed voltage. The conversion from AC to DC for a single phase is

about 90% and thus 110V AC results in about 100V DC.   The unit has needle gauges for both DC volts and amps.   As the voltage is changed, the amps change according to the conductivity (resistance) of the load which is the solution being tested. The needle gauges indicate the nominal voltage and nominal amperage. The power calculated by multiplying these two quantities is the nominal power.

The electrodes of the EC system may be powered in different ways depending on which electrodes are directly connected to the power supply.   The simplest configuration is when power is sent to the two outside blades (of the 9 present). This is depicted below as configuration 1. Configuration 2 has the outside blades connected to the positive polarity of the power supply and the middle blade to the negative (or vice versa).   In this situation the resistance between the positive and negative electrodes (the number of solution gaps) is one half what it is in configuration 1.   Configuration 3 and 4 increase the number of directly powered electrode blades and provide less resistance than configurations 1 and 2. The usefulness in employing different configurations is that amperage may be changed for a given voltage and a given solution (load). In poorly conductive (low salinity) solutions, little amperage is generated at high voltage levels.   By changing the power configuration, higher amperages may be attained.

```
                        +         --                           +    --    +
Configuration 1         | | | | | | | | |     Configuration 2  | | | | | | | | |

                        +  --  +  --   +                       +--+ --+-- +-- +
Configuration 3         | | | | | | | | |     Configuration 4  | | | | | | | | |
```
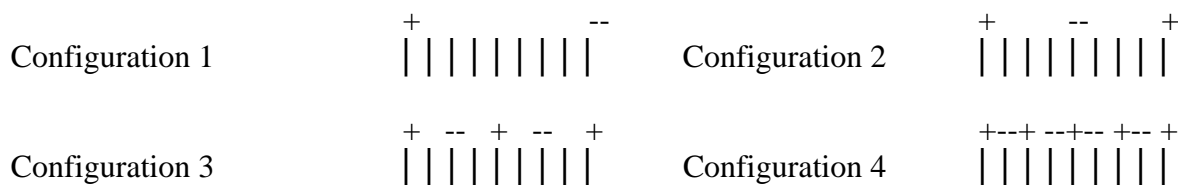
3.2.4.3 Residence Time: Flow through the EC cell was driven by peristaltic pump that had a flow control knob with numeric settings.   The available flow range was from 790 ml/min at a setting of 4 to 1,665 ml/min at a setting of 8.   The EC chamber had a volume with electrodes present of 290 ml.   The residence time or the solution exposure time is simply the EC chamber volume divided by the flow rate.   Some studies varied the flow rate and thus the residence time to see its effect on contaminant removal. The following figure shows the residence time as a function of pump setting.   Most runs were made at a pump setting of 8.

3.2.4.4 Number of Passes: In some studies the treated solution was run through the EC system a second time to determine the effects on contaminant removal.   While this increases the effective residence time of solution it also introduces a time delay between exposures of the solution to the electrodes.   During this time, chemical and physical changes initiated by the first exposure are ongoing.   This may include chemical reactions, growth of floc, cooling, etc.

3.2.5   Measurements

3.2.5.1 Turbidity Levels: Turbidity measurements offered a simply and quick means of determining changes in suspended solids levels over the course of the experimental runs. These suspended solids included those present in the initial feed solution and those created due to the coagulation / flocculation and other changes brought about by the EC treatment.
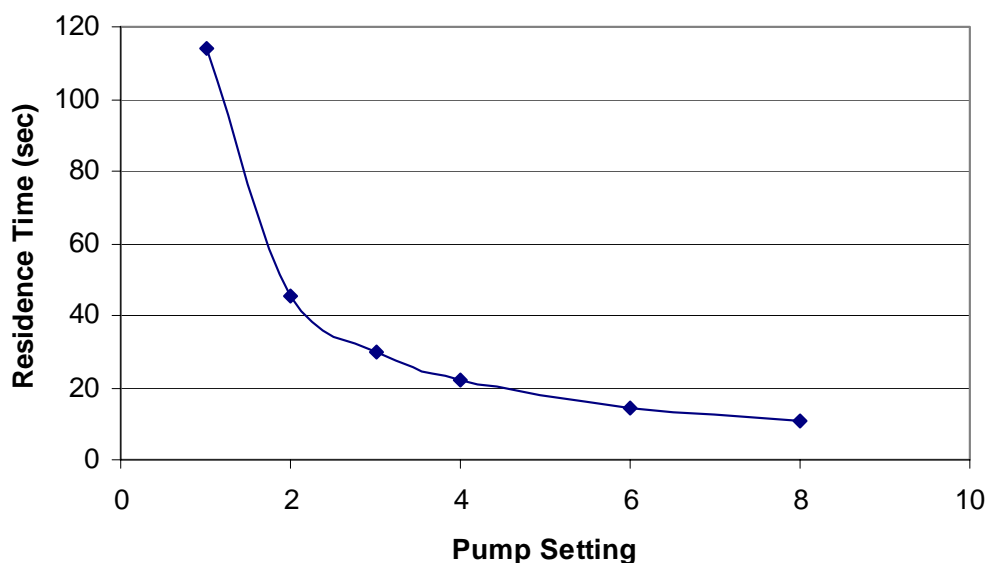
Turbidity was measured using a HACH 2100P portable turbidimeter. Samples are put into a clean 25 ml glass vial and inserted into the turbidimeter for a determination of turbidity (NTUs) based on light passage through the vial. The turbidimeter is calibrated as needed against turbidity standards. Readings are affected the cleanliness of glass vials and the presence of scratches. The test solutions need to be free of bubbles.

Turbidity readings for various waters and conditions are listed below.

Condition	NTU
DI water	0.13
Tap water	0.75 to 0.98
Lowest reading of treated water	0.06
Highest reading of feed solution	610

3.2.5.2 ORP – Oxidation-Reduction Potential: ORP was measured by a hand-held HACH Pocket Pal ORP tester. The reading is sensitive to the oxygen level in the solution and thus stirring and changes in the oxygen levels with time including those due to temperature effects. Thus ORP values drifted with time and the assignment of a specific number to a measurement was somewhat arbitrary. However, ORP measurements were quantitative enough to provide useful indications of the general condition of the solutions. Measured values determined in the studies ranged from a -727 to +580.

3.2.5.3 pH: In very early runs, pH was measured by pH paper. Indicated values were likely no better than 0.5 pH units. Most of the pH measurements were done using a HACH Sension2 Portable pH/ISE meter with platinum pH electrode. Measured values determined in the studies ranged from 3.0 to 11.0

3.2.5.4 Total Solids: Measurement of total solids (TS) provided a means of following the overall material balance during runs. Ten ml of solution was pipetted into a pre-weighed metal

weighing pan and then put in the drying oven to evaporate the water. Such samples were taken of the feed solution, the treated solution, and the treated and filtered solution. Two separate samples were taken for all determinations.

3.2.5.5 Color: Color changes upon EC treatment and filtering were common and provided a visible indication of the effects of different conditions on the solution. No attempt was made to quantify the colors. Color was used as a simple qualitative indicator.

3.2.5.6 Temperature: The temperature of the solutions at various steps in the EC runs was documented. The temperature was measured by a thermometer immersed in the solution.

3.2.5.7 Contaminant Removal: The means of measurement of contaminant removal from solution depended on the particular contaminant. The turbidity measurements just mentioned were used to determine the removal of suspended solids from solution. Calcium levels were measured in-house using a HACH digital titrator with a calcium reagent kit. Outside analytical services were used for other determinations.

Analytical methods used by the various analytical services included:

- For most metals: EPA method 200.7/6010B (ICP)
- Cs, As, Cd EPA method 200.8/6020 (ICP/MS)
- Phosphate, nitrate EPA method 300.0 (Ion chromatography)
- Perchlorate EPA method 314 (Ion chromatography)

The Analytical services used included:
- Aqua Tech Environmental Laboratories, Inc., Tucson
- Aqua Tech Environmental Laboratories, Inc., Marion, OH
- CDPH&E Laboratory Services Division, Denver
- Huffman Laboratories

3.2.6 Comments on EC Run Protocol

In early runs the EC treated solution was collected in a series of containers to enable determination of any change in treatment effects with processing time. Measurements were made of temperature, pH, ORP, and turbidity on feed solution and on each of the collected treated portions. Visual observations of the treated portions were also recorded and included qualitative amount of floc, color, rapidity of settling, etc.

These findings and observations allowed later protocols to be simplified and run times to be significantly reduced. More specifically, later protocols called for the first treated residence volume to be discarded but for the remaining treated solution to be collected as the representative treated solution. The various measurements were then done only on the larger collected sample – saving much time.

Aliquots of the treated solution were taken to allow the measurements mentioned.   The remainder of the treated solution was filtered by gravity using a 11-micron Whatman No. 1 filter. The same measurements were made on the filtered sample.

Following EC runs, the EC reaction chamber was flushed with water and then cleaned using a soap solution and wire brush.   Periodically, a 10% solution of HCl was used to clean surfaces, followed by extensive flushing with water.

The metal electrodes (blades) were cleaned by rinsing, squirting with 10% HCl solution, and hand scrubbing to remove surface films built up as a result of the EC run.

3.2.7   Membrane Studies

A primary objective of the project was to define the best application of the EC technology within the context of providing pretreatment to reverse osmosis systems.   Over the last several years it has become apparent from the literature and from field experience that the best pretreatment to RO systems is a low-pressure membrane – either UF or MF.   The question to be resolved became 'can EC provide beneficial pretreatment for a UF/RO (or MF/RO) membrane system? And more specifically 'can EC provide beneficial pretreatment for a UF (or MF) membrane?'

One limitation of UF and MF membranes is their susceptibility to high suspended solids feeds especially when the solids have an organic nature. While cartridges filters can be placed in front of the UF or MF membrane, they can become rapidly clogged.

The project work initially focused on EC removal studies and after several studies the high removal rates of suspended solids suggested that this solids removal application of EC was likely the most promising and beneficial aspect of pretreatment.

The second type of laboratory tests involved membrane studies using a simple dead-end flow cell. These studies helped to demonstrate the fouling potential of a UF membrane and the effect of EC pretreatment on the UF flux.

3.2.7.1 Amicon Stirred Cell : The Amicon stirred cell is a dead-end flow device where the test solution is pushed through a circular (47 mm diameter) and flat membrane mounted at the bottom of the test cell.   A stirring rod mounted in the top portion of the test cell provides mixing of the solution when the cell is placed on a magnetic stirrer device.   The cell has a volume of about 100 ml and can be pressurized up to 80psi.   Permeate from the membrane initially enters a thin porous support media and then flows out a small port to which a flexible tube is attached. The pressure source was nitrogen gas from a gas cylinder attached with a standard gas tank regulator to control the gas pressure.

3.2.7.2 Membranes: The membrane used in all of the studies was an Osmonic's polysulfone YMEWSP1905 UF membrane with nominal molecular weight cutoff of 60K. The flux and material properties of the membrane are similar to the UF membrane planned for use in the large military demonstration units.

3.2.7.3 General Membrane Test Protocol:
- The 47 mm diameter membranes were cut from the larger flat sheet samples purchased from Osmonics.
- The membrane piece to be used was wet by dipping it in 50:50 alcohol:water mixture for 10 seconds, followed by a 10 second dip in a 10:90 alcohol:water mixture and finally for 10 seconds in a 100% DI water solution.
- The bottom part of the test cell is filled with water to avoid trapping of air bubbles in the initial flow and the wetted membrane is installed.
- The middle part of the tests cell, the cell body, is attached to the bottom portion and filled with 60 ml of test solution
- The upper portion of the test cell, connected to the pressure source, is attached and the complete cell is placed in the cell holder.
- The completed cell is placed on the magnetic stirrer.
- The magnetic stirrer is turned on.
- A pre-weighed weighing pan is placed to collect permeate.
- The pressure relief valve is closed.
- The magnetic stirrer is turned on.
- The cell is pressurized and the clock started.
- The initial 10 seconds of permeate are collected.
- Another pre-weighed weighing pan is placed under the permeate tube at 30 seconds to collect the permeate for the time period of 30 to 40 seconds.
- The pressure is turned off and the pressure relief valve on the test cell is opened to depressurize the cell.
- The cell is taken apart and cleaned, if necessary.
- The weighing tins are weighed to determine the volume flow occurring in the 10 second interval.

3.2.7.4 Comments on the Protocol: The protocol used had some arbitrary aspects to it and was not meant to be quantitative.   First, the flux through the membranes showed a pronounced time effect, decreasing with time due to pressure effects and membrane fouling.   Second, there was an effect on the membrane flux of a given piece of membrane resulting from de-pressurizing the test cell and re-pressurizing the test cell. Third, there was a large variability between 47 mm diameter circles cut from the same membrane sheet.

In an effort to minimize the variability occurring from the first two factors, the test protocol was followed closely to provide the best opportunity for reproducibility of results.   In addition, all membrane fluxes were normalized by the initial DI water flux.

Past use of a similar test protocol has shown that this approach yields useful, fairly reproducible, semi-quantitative data.   Thus the measured flux values are not of interest; it is the change in the normalized flux values that provide helpful information.

3.2.7.5 Amicon Membrane Fouling Tests: The series of fouling tests was developed several years ago in a previous contract.   The series consists of a sequence of four flux determinations:

- DI water flux – the flux of the membrane is determined using DI water.
- DI water flux after exposure of membrane to the test solution – the flux of the membrane is determined after dipping the membrane into the test solution for 10 seconds and rinsing the surface of the membrane with DI water.
- Test solution flux – the DI water is replaced with test solution and the membrane flux is determined
- DI water flux – the remaining test solution is discarded and the surface of the membrane is flushed with DI water to remove possible reversible fouling effects.   The cell is then filled with DI water to determine the DI water flux.

From past fouling studies, the flux variability in the small (47 mm) membrane circles can be large. To normalize the various membrane flux determinations all fluxes are divided by the pure water flux as determined by the initial DI water flux test. This test must be the first test run to assure that the membrane is not contaminated by any species form the test solution.   The second flux determination provides an indication of the irreversible fouling due to exposure of the membrane to the test solution.   It can be considerable for foulants having a high affinity for the membrane material. The third run determines the flux due to running the test solution through the membrane.   The final and fourth flux determination is done with DI water. It provides an indication of the degree of reversible fouling present.

3.2.8   Energy Cost Calculation

The power used by the EC system is of interest as it is in indicator of the energy use - major component of the operating cost.   The power used in the EC runs can be estimated from indicated and documented operation parameters. The power supply has two needle gages giving readings of the DC voltage and amperage going to the EC cell.   These values are 'nominal' values in that these indicated values but may differ from actual values due to 1) not being true RMS (root mean square) values and 2) the way the power supply regulates the power going to the EC system.   Several attempts were made to determine the true power usage, however, the issue was never fully resolved.

Thus the following calculation sequence is based on the use of nominal volts and amps as indicated on the power supply gages.

Energy cost ($ / volume)   =   watts (volts times amps)

                                                                 * energy cost ($ / kWh)

                                                                 / flow (volume / h)

The watts are calculated using the nominal values (and converted to kilowatts). The energy cost is a chosen value, typically from $0.03 to $0.10/kWh.   The flow is calculated based on the pump speed.   The flow corresponding to the pump settings was discussed earlier.

CHAPTER 4.

RESULTS

4.1 EC DATA SUMMARY

The results of the electrocoagulation runs are discussed first followed by a discussion of the membrane studies.

Table 4.1 is a tabulation of all the EC runs made along with their variable and parameter values. The runs are given in numerical order, which was the chronological order also. Table 4.2 provides a KEY for the terms used in Table 4.1. As described in Table 4.2 there were several different base or background solutions used in the studies. Most of them were of a TDS level close to 1,000 mg/L. Table 4.3 is a summary of the removal results from the various EC studies.

The various studies and runs are discussed next by contaminant category.

4.1.1 Suspended Solids Removal

The runs studying removal of suspended solids represent the Group I contaminants. One reason for studying this group of contaminants first was that the removal results are indicated by turbidity measurements that were simple to do and offered rapid feedback on the removal results.

The specific runs of Table 4.1 and Table 4.3 that focused on suspended solid removals include:

Run numbers   specific contaminant
- R1   latex paint
- R2, R4-R22   oil-water emulsions
- R3, R25   tannic and humic acid mixture
- R23, R24   silt
- R96-R102   hydrocarbon condensate

4.1.1.1 Latex Paint – Mock Solution: This first run was conducted simply because latex paint was known to give a dramatic visual result upon EC treatment. A photograph of this initial run is shown below. The untreated feed is on the right; the treated and filtered solution is on the left. As with all the runs made, the 'after' results mean after treatment and after gravity filtering using an 11 micron paper filter. The solids filtered out are visible on filter paper lining the strainer.

The measured removal of turbidity was 99.61 percent.

4.1.1.2 Oil-Water Emulsions – Mock Solutions: These many runs provided the means to investigate the effects of several system variables and to refine the initial testing protocol. Note that in Table 4.3 initial runs were made at relatively high power levels and later runs were made with decreasing power levels. Very high removal levels (> 99.5%) with one exception (98.3% in run

Table 4.1. Tabulation of Electrocoagulation Data (see Table 4.2. for KEY)

RUN #	Blades	Base Solution	Contaminate(s))	Feed TDS	Special Condition	Pump Setting	Circuit Setup	Nominal Voltage	Nominal Amperage	Nominal Power	pH PRE	pH POST	NTU PRE	NTU POST	% NTU REMOVAL	ORP PRE	ORP POST	Ca++ PRE	Ca++ POST	% Ca++ REMOVAL	Pre-TS (mg/L)	Post-TS (mg/L)	% CHANGE TS
R1	Al	1	LATEX PAINT			4	1	100	13	1300	6	---	494	0.4	-99.9	---	---	463	---	---			-20.50
R2	Al	1	100 ppm OIL		+10 ppm Tannic & Humic acid	4	1	100	15.5	1550	6	---	104	0.41	-99.6	---	---	463	---	---			-24.15
R3	Al	1	10 ppm Tannic/Humic acid			4	1	100	15	1500	6	6.5	5.47	0.66	-87.9	---	---	463	---	---			
R4	Al	1	100 ppm OIL			4	1	100	13	1300	6	6.5	34.7	0.59	-98.3	---	---	463	---	---			-20.20
R5	Al	1	100 ppm OIL		repeat	4	1	100	13	1300	6	6	75.2	0.42	-99.4	---	---	463	327.9	-29.2			-15.09
R6	Al	1	100 ppm OIL		repeat	4	1	100	13	1300	6	6.5	69.9	0.27	-99.6	153	-148	463	---	---			-16.96
R7	Al	1	100 ppm OIL		repeat	4	1	100	13	1300	6	6	90.7	0.24	-99.7	223	-75	463	309.5	-33.2			-16.93
R8	Fe	1	100 ppm OIL		Fe blades	4	1	90	18.5	1665	6	6.5	70.4	0.15	-99.8	173	-95	463	450.9	-2.6			-0.68
R9	Fe	1	100 ppm OIL		repeat	8	1	100	15	1500	6	7.5	76	0.42	-99.4	152	-227	463	***				0.22
R10	Fe	1	100 ppm OIL		high salinity (~4000 ppm)	8	1	50	9	450	6	8.5	88.6	0.25	-99.7	183		463	487.8	5.4			2.43
R11	Fe	2	100 ppm OIL		low salinity (~1000 ppm)	8	1	50	3	150	6	8	56.7	0.13	-99.8	---	---	115.8	121.9	5.3			9.09
R12	Fe	3	100 ppm OIL		med salinity (~2000 ppm)	8	1	50	5	250	6	8	89.6	0.15	-99.8	---	---	231.5	255.2	10.2			6.98
R13	Fe	1	100 ppm OIL		low power	8	1	25	4	100	6	7.5	73.3	0.16	-99.8	137	-268	463	516.5	11.6			2.27
R14	Fe	1	100 ppm OIL		very low power	8	1	5	0.9	4.5	6	7	42.2	0.11	-99.7	202	-185	463	528.8	14.2			1.31
R15	Fe	1	200 ppm OIL		higher OIL content	8	1	5	0.75	3.75	6	7	208	0.15	-99.9	206	-176	463	547.2	18.2			1.10
R16	Fe	4	100 ppm OIL		+0.3g/L NaHCO3	8	1	5	0.7	3.5	6.5	7	51.2	0.17	-99.7	156	-295	463	506	9.3			-1.04
R17	Fe	5	100 ppm OIL		+0.3g/L NaHCO4	8	1	5	0.75	3.75	8.06	8.5	127	0.33	-99.7	110	-150	463	434.5	-6.2			-0.22
R18	Fe	4	100 ppm OIL		+0.3g/L NaHCO5 low temp - 8C	8	1	5	0.6	3	7.92	8.7	74.6	0.34	-99.5	171	-88	463	***				1.04
R19	Fe	6	100 ppm OIL		higher temp - 22.7C	8	1	100	0.4	40	7.88	8.5	136	0.2	-99.9	467	-103	---	8.2				-50.00
R20	Fe	6	100 ppm OIL		high temp - 50C	8	1	100	0.4	40	7.99	8.68	132	0.12	-99.9	180	30	---	8.2				153.33
R21	Fe	1	100 ppm OIL		high flow	2x '8'	1	5	0.6	3	6.3	8.4	64.7	0.19	-99.7	173	136	463	514.4	11.1			-1.54
R22	Al	1	100 ppm OIL		high flow	2x '8'	1	5	0.4	2	6.34	7.01	68.4	0.31	-99.5	165	133	463	537	16.0			-1.10
R23	Fe	1	SILT MIXTURE			8	1	5	1	5	8.14	7.36	612	0.3	-100.0	44	-115	463	537	16.0			-28.85
R24	Fe	4	---		+0.3g/L NaHCO5 pH = 11.11	8	1	5	1	5	11.11	11.23	117	0.42	-99.6	60	-17	463	373	-19.4	4995	4945	-1.0
R25	Fe	1	10 ppm Humic/Tannic acid			4	1	90	14	1260	7.91	8.38	5.07	0.34	-93.3	---	---	463	***				

OREGON (Low Amperage)

RUN #	Blades	Base Solution	Contaminate(s))	Feed TDS	Special Condition	Pump Setting	Circuit Setup	Nominal Voltage	Nominal Amperage	Nominal Power	pH PRE	pH POST	NTU PRE	NTU POST	% Removal (Turbidity)	ORP PRE	ORP POST	Ca++ PRE	Ca++ POST	% Ca++ REMOVAL	Pre-TS (mg/L)	Post-TS (mg/L)	% CHANGE TS
R26	Fe	7	As, Si			8	1	100	0.6	60	3.33	5.4	29.9	26.8	-10.4	303	64	---	***		555	465	-16.2
R27	Fe	7	As, Si		High amp	8	1	25	7	175	7.64	8.9	0.1	2.6	---	85	21	---			8695	8340	-4.1
R28	Fe	7	As, Si		Low amp	8	1	5	1	5	7.74	8.33	0.1	5.97	---	242	-287			---	8695	8585	-1.3

MOCK SOLUTION (As & Si)

RUN #	Blades	Base Solution	Contaminate(s))	Feed TDS	Special Condition	Pump Setting	Circuit Setup	Nominal Voltage	Nominal Amperage	Nominal Power	pH PRE	pH POST	NTU PRE	NTU Post	% Removal (Turbidity)	ORP PRE	ORP POST	Ca++ PRE	Ca++ POST	% Ca++ REMOVAL	Pre-TS (mg/L)	Post-TS (mg/L)	% CHANGE TS
R29	Fe	8	As, Si		Low amp	8	1	27	1	27	9.33	9.7	2.21	---	---	---	---	78.3	***		680	1125	65.4
R30	Fe	8	As, Si		High amp	8	1	98	4	392	9.33	9.66	2.21	0.43	---	---	---	78.3	***		680	960	41.2

HIGH pH (Ca++ Removal Study)

RUN #	Blades	Base Solution	Contaminate(s))	Feed TDS	Special Condition	Pump Setting	Circuit Setup	Nominal Voltage	Nominal Amperage	Nominal Power	pH PRE	pH POST	NTU Pre	NTU POST	% Removal (Turbidity)	ORP PRE	ORP POST	Ca++ PRE	Ca++ POST	% Ca++ REMOVAL	Pre-TS (mg/L)	Post-TS (mg/L)	% CHANGE TS
R31	Fe	8	HIGH pH = 12		set aside for 10 min before EC treatment	8	1	20	2	40	12	11.97	251	0.29	-99.9	75	-325	78.3	***		5585	2290	-59.0
R32	Fe	8	HIGH pH = 12		set aside for 77 min before EC treatment	8	1	24	2	48	11.93	11.91	279	0.42	-99.8	115	-357	78.3	***		6185	2145	-65.3

PRODUCT WATER PRODUCTION FOR SEPA (SM5)

RUN #	Blades	Base Solution	Contaminate(s))	Feed TDS	Special Condition	Pump Setting	Circuit Setup	Nominal Voltage	Nominal Amperage	Nominal Power	pH PRE	pH POST	NTU PRE	NTU POST	% Removal (Turbidity)	ORP PRE	ORP POST	Ca++ PRE	Ca++ POST	% Ca++ REMOVAL	Pre-TS (mg/L)	Post-TS (mg/L)	% CHANGE TS
R33	Fe	8	100 ppm OIL		for run SM5	8	1	25	1	25	8.4	8.93	81.3	0.5	**-99.4**	335	-123	78.3	***		1010	915	-9.4

MOCK SOLUTION (As & Si)

RUN #	Blades	Base Solution	Contaminate(s))	Feed TDS	Special Condition	Pump Setting	Circuit Setup	Nominal Voltage	Nominal Amperage	Nominal Power	pH PRE	pH POST	NTU PRE	NTU POST	% Removal (Turbidity)	ORP PRE	ORP POST	Ca++ PRE	Ca++ POST	% Ca++ REMOVAL	Pre-TS (mg/L)	Post-TS (mg/L)	% CHANGE TS
R34	Fe	8	As/Si			8	2	42	10	420	7.07	9.2	---	---	---	---	---	78.3			1090	1155	6.0
R35	Fe	8	As/Si		+ NaCl	8	2	24	10	240	7.68	8.9	---	---	---	---	---	78.3			1760	1780	1.1

OREGON (single pass)

RUN #	Blades	Base Solution	Contaminate(s))	Feed TDS	Special Condition	Pump Setting	Circuit Setup	Nominal Voltage	Nominal Amperage	Nominal Power	pH PRE	pH POST	NTU PRE	NTU POST	% Removal (Turbidity)	ORP PRE	ORP POST	Ca++ PRE	Ca++ POST	% Ca++ REMOVAL	Pre-TS (mg/L)	Post-TS (mg/L)	% CHANGE TS
R36	Fe	7	As, Si		med power	8	3	12	10	120	3.27	6.61	---	---	---	---	---				630	345	-45.2
R37	Fe	7	As, Si		high power	8	2	24	17.5	420	3.27	7.77	---	---	---	---	---				630	290	-54.0

METAL SOUP (I)

RUN #	Blades	Base Solution	Contaminate(s))	Feed TDS	Special Condition	Pump Setting	Circuit Setup	Nominal Voltage	Nominal Amperage	Nominal Power	pH PRE	pH POST	NTU PRE	NTU POST	% Removal (Turbidity)	ORP PRE	ORP POST	Ca++ PRE	Ca++ POST	% Ca++ REMOVAL	Pre-TS (mg/L)	Post-TS (mg/L)	% CHANGE TS
R38	Fe	8	METAL SOUP		ph 7/ med power	8	2	52	8	416	6.98	9.38	40.1	0.21	-99.5	258	-238				735	540	-26.5
R39	Fe	8	METAL SOUP		ph 8/ lo power	8	2	4	1	4	8.12	9.16	42.6	0.17	-99.6	169	-162				880	690	-21.6
R40	Fe	8	METAL SOUP		ph 8/ hi power	8	2	90	15	1350	8.12	9.82	42.6	0.17	-99.6	169	-316				880	740	-15.9
R41	fee	8	METAL SOUP		ph 6/ lo power	8	2	5	1	5	6.04	6.83	36.4	0.41	-98.9	548	-82				745	560	-24.8
R42	Fe	8	METAL SOUP		ph 6/ hi power	8	2	90	15	1350	6.04	7.55	36.4	1.13	-96.9	548	-208				745	590	-20.8

RADIONUCLIDE STUDY

RUN #	Blades	Base Solution	Contaminate(s))	Feed TDS	Special Condition	Pump Setting	Circuit Setup	Nominal Voltage	Nominal Amperage	Nominal Power	pH PRE	pH POST	NTU PRE	NTU POST	% Removal (Turbidity)	ORP PRE	ORP POST	Ca++ PRE	Ca++ POST	% Ca++ REMOVAL	Pre-TS (mg/L)	Post-TS (mg/L)	% CHANGE TS
R43	Fe	9	Radionuclide Mix	1000 mg/L	ph 6/ lo power	8	2	2	1	2	6.05	10.68	0.09	0.07	-22.2	530	-245				1115	1320	18.4
R44	Fe	9	Radionuclide Mix	1000 mg/L	ph 6/ hi power	8	2	50	15	750	6.05	10.16	0.09	0.18	100.0	530	-245				1115	1250	12.1
R45	Fe	9	Radionuclide Mix	1000 mg/L	ph 8/ lo power	8	2	2	1	2	8.1	10.55	0.09	0.08	-11.1	330	-283				1130	1355	19.9
R46	Fe	9	Radionuclide Mix	1000 mg/L	ph 8/ hi power	8	2	50	15	750	8.1	10.38	0.09	0.11	22.2	330	-210				1130	1300	15.0

BENZILIC ACID (for TOC analysis)

RUN #	Blades	Base Solution	Contaminate(s))	Feed TDS	Special Condition	Pump Setting	Circuit Setup	Nominal Voltage	Nominal Amperage	Nominal Power	pH PRE	pH POST	NTU PRE	NTU POST	% Removal (Turbidity)	ORP PRE	ORP POST	Ca++ PRE	Ca++ POST	% Ca++ REMOVAL	Pre-TS (mg/L)	Post-TS (mg/L)	% CHANGE TS
R47	Fe	8	Benzilic Acid		NOT STERILIZED (no analysis)	8	2	81	15	1215	7.85	9.17	5.14	0.55	-89.3	254	-255	78.3			900	915	1.7
R48	Fe	10	Benzilic Acid		lo pH/lo amp	8	2	4	1	4	5.95	10.74	0.11	0.06	-45.5	349	-230				785	925	17.8
R49	Fe	10	Benzilic Acid		lo pH/hi amp	8	2	78	15	1170	5.95	10.21	0.11	0.14	27.3	349	-270				865	885	2.3
R50	Fe	10	Benzilic Acid		hi pH/hi amp	8	2	68	15	1020	8	10.99	0.35	0.17	-51.4	366	-367				835	1035	24.0

OIL WATER EMULSION (for TOC analysis)

RUN #	Blades	Base Solution	Contaminate(s))	Feed TDS	Special Condition	Pump Setting	Circuit Setup	Nominal Voltage	Nominal Amperage	Nominal Power	pH PRE	pH POST	NTU PRE	NTU POST	% Removal (Turbidity)	ORP PRE	ORP POST	Ca++ PRE	Ca++ POST	% Ca++ REMOVAL	Pre-TS (mg/L)	Post-TS (mg/L)	% CHANGE TS
R51	Fe	1	100 ppm OIL		for TOC	8	1	5	0.75	3.75	5.77	10.75	98.7	0.12	-99.9	297	-275	463			4760	4740	-0.4

RED TIDE SAMPLE from Port HUENEME

RUN #	Blades	Base Solution	Contaminate(s))	Feed TDS	Special Condition	Pump Setting	Circuit Setup	Nominal Voltage	Nominal Amperage	Nominal Power	pH PRE	pH POST	NTU PRE	NTU POST	% Removal (Turbidity)	ORP PRE	ORP POST	Ca++ PRE	Ca++ POST	% Ca++ REMOVAL	Pre-TS (mg/L)	Post-TS (mg/L)	% CHANGE TS
R52	Fe	11	Port Hueneme	Sea Water		8	1	4	2	8	7.71	8.65	1.62	1.17	-27.8	400	-266				35390	35675	0.8
R53	Fe	11	Port Hueneme	Sea Water		8	1	20	15	300	7.71	9	1.62	1.91	17.9	400	-218				35390	35635	0.7

OREGON (1-PASS & 2-PASS)

RUN #	Blades	Base Solution	Contaminate(s))	Feed TDS	Special Condition	Pump Setting	Circuit Setup	Nominal Voltage	Nominal Amperage	Nominal Power	pH PRE	pH POST	NTU PRE	NTU POST	% Removal (Turbidity)	ORP PRE	ORP POST	Ca++ PRE	Ca++ POST	% Ca++ REMOVAL	Pre-TS (mg/L)	Post-TS (mg/L)	% CHANGE TS
R54	Fe	7	As, Si		1 pass	8	2	98	3.5	343	3.03	6.63	29.5	0.49		310	-60	---	---	---	585	240	-59.0
R55	Fe	7	As, Si		2nd pass	8	2	98	2	196	3.03	7.2	29.5	5.16		310	-60	---	---	---	585	165	-71.8
R56	Fe	7	As, Si		1 pass	8	3	12	10	120	3.03	5.43	29.5	6.51		310	-4	---	---	---	585	560	-4.3
R57	Fe	7	As, Si		2nd pass	8	3	16	10	160	3.03	6.79	29.5	3.48		310	-5	---	---	---	585	390	-33.3

METAL SOUP (1-PASS & 2-PASS; Analytes: Ba, Cr, & Sr)

RUN #	Blades	Base Solution	Contaminate(s))	Feed TDS	Special Condition	Pump Setting	Circuit Setup	Nominal Voltage	Nominal Amperage	Nominal Power	pH PRE	pH POST	NTU PRE	NTU POST	% Removal (Turbidity)	ORP PRE	ORP POST	Ca++ PRE	Ca++ POST	% Ca++ REMOVAL	Pre-TS (mg/L)	Post-TS (mg/L)	% CHANGE TS
R58	Fe	8	Metal Soup	874 mg/L	1 pass	8	2	58	8	464	6.92	8.55	44.5	0.15		290	80	58.2	45.9	-21.1	780	850	9.0
R59	Fe	8	Metal Soup	874 mg/L	2nd pass	8	2	52	8	416	6.92	9.76	44.5	0.15		290	-89	58.2	16.4	-71.8	780	825	5.8

ISOLATED Sr:Cr RATIO

RUN #	Blades	Base Solution	Contaminate(s))	Feed TDS	Special Condition	Pump Setting	Circuit Setup	Nominal Voltage	Nominal Amperage	Nominal Power	pH PRE	pH POST	NTU PRE	NTU POST	% Removal (Turbidity)	ORP PRE	ORP POST	Ca++ PRE	Ca++ POST	% Ca++ REMOVAL	Pre-TS (mg/L)	Post-TS (mg/L)	% CHANGE TS
R60	Fe	8	Sr:Cr (100:10 ppm)	874 mg/L	10:1 Ratio	8	2	52	8	416	7.04	8.88	0.09	0.19		434	-155	***	57.4	#VALUE!	710	835	17.6 #DIV/0!
R61	Fe	8	Sr:Cr (50:50 ppm)	874 mg/L	5:5 Ratio	8	2	52	8	416	7	9.36	0.09	0.54		443	-182	85.7	36.9	-56.9	810	835	3.1 #DIV/0!
R62	Fe	8	Sr:Cr (10:100 ppm)	874 mg/L	1:10 Ratio	8	2	52	8	416	7	9.95	0.09	0.16		458	-220	65.6	10.2	-84.5	855	540	-36.8

INDIVIDUAL METALS STUDY

RUN #	Blades	Base Solution	Contaminate(s))	Feed TDS	Special Condition	Pump Setting	Circuit Setup	Nominal Voltage	Nominal Amperage	Nominal Power	pH PRE	pH POST	NTU PRE	NTU POST	% Removal (Turbidity)	ORP PRE	ORP POST	Ca++ PRE	Ca++ POST	% Ca++ REMOVAL	Pre-TS (mg/L)	Post-TS (mg/L)	% CHANGE TS
R63	Fe	8	Cr (10 ppm)	874 mg/L	Standard TDS	8	2	52	8	416	6.97	8.79	0.21	0.29		265	-240	***	55.7	#VALUE!	740	935	26.4
R64	Fe	8	Cr (10 ppm)	35,000 mg/L	HIGH TDS	8	2	<1	8	#VALUE!	6.95	9.05	0.15	0.13		210	-240	***	75.4	#VALUE!	33255	33910	2.0
R65	Fe	8	Ba (10 ppm)	874 mg/L		8	2	45	8	360	6.93	8.78	0.16	0.3		209	-185	66	45.1	-31.7	1020	1030	1.0
R66	Fe	8	Cd (10 ppm)	874 mg/L		8	2	50	8	400	7.07	8.91	0.2	0.73		266	-150	67.2	52.1	-22.5	1025	1175	14.6
R67	Fe	8	Sr (10 ppm)	874 mg/L	Standard TDS	8	2	48	8	384	7	8.84	0.15	0.51		242	-119	73	63.5	-13.0	985	1150	16.8
R68	Fe	8	Sr (10 ppm)	35,000 mg/L	HIGH TDS	8	2	<1	8	#VALUE!	7	9.27	0.16	1.25		206	-170	81.2	32.8	-59.6	34185	33925	-0.8

MAGNESIUM BLADE STUDY (with MOCK water)

RUN #	Blades	Base Solution	Contaminate(s))	Feed TDS	Special Condition	Pump Setting	Circuit Setup	Nominal Voltage	Nominal Amperage	Nominal Power	pH PRE	pH POST	NTU PRE	NTU POST	% Removal (Turbidity)	ORP PRE	ORP POST	Ca++ PRE	Ca++ POST	% Ca++ REMOVAL	Pre-TS (mg/L)	Post-TS (mg/L)	% CHANGE TS
R69	Mg	8	Si (100 ppm)	874 mg/L	8 Amp/High pH	8	2	40	8	320	10.95	11.54	0.54	0.47		23	-325	30.7	3.3	-89.3	995	935	-6.0
R70	Mg	8	Si (100 ppm)	874 mg/L	15 Amp/High pH	8	2	71	15	1065	10.95	11.54	0.54	0.72		23	-352	30.7	3.7	-87.9	995	1250	25.6
R71	Mg	8	Si (100 ppm)	874 mg/L	8 Amp/ Neutral pH	8	2	39	8	312	8.65	10.35	0.11	0.08		179	-230	27.2	4.1	-84.9	1020	855	-16.2

RUN #	Blades	Base Solution	Contaminate(s)	Feed TDS	Special Condition	Pump Setting	Circuit Setup	Nominal Voltage	Nominal Amperage	Nominal Power	pH PRE	pH POST	NTU PRE	NTU POST	% Removal (Turbidity)	ORP PRE	ORP POST	Ca++ PRE	Ca++ POST	% Ca++ REMOVAL	Pre-TS (mg/L)	Post-TS (mg/L)	% CHANGE TS
R72	Mg	8	Si (100 ppm)	874 mg/L	15 Amp/Neutral pH	8	2	70	15	1050	8.65	10.7	0.11	2.5		179	-269	27.2	4.1	-84.9	1020	1535	50.5

Silica Removal with IRON BLADES on MOCK WATER (Si) (Control for Mg: R71 & R72)

RUN #	Blades	Base Solution	Contaminate(s)	Feed TDS	Special Condition	Pump Setting	Circuit Setup	Nominal Voltage	Nominal Amperage	Nominal Power	pH PRE	pH POST	NTU PRE	NTU POST	% Removal (Turbidity)	ORP PRE	ORP POST	Ca++ PRE	Ca++ POST	% Ca++ REMOVAL	Pre-TS (mg/L)	Post-TS (mg/L)	% CHANGE TS
R73	Fe	8	Si (100 ppm)	874 mg/L	8 Amp/Neutral pH	8	2	43	8	344	8.65	9.3	0.11	0.65		179	-123	27.2	12.7	-53.3	1020	815	-20.1
R74	Fe	8	Si (100 ppm)	874 mg/L	15 Amp/Neutral pH	8	2	76	15	1140	8.65	9.58	0.11	0.17		179	-195	27.2	9.4	-65.4	1020	1085	6.4

MAGNESIUM BLADE STUDY (with REAL water)

RUN #	Blades	Base Solution	Contaminate(s)	Feed TDS	Special Condition	Pump Setting	Circuit Setup	Nominal Voltage	Nominal Amperage	Nominal Power	pH PRE	pH POST	NTU PRE	NTU POST	% Removal (Turbidity)	ORP PRE	ORP POST	Ca++ PRE	Ca++ POST	% Ca++ REMOVAL	Pre-TS (mg/L)	Post-TS (mg/L)	% CHANGE TS
R75	Mg	12	Si, Ca	1120 mg/L	8 Amp	8	2	40	8	320	7	10.35	0.55	0.1		230	-119	188.6	155.8	-17.4	1250	1025	-18.0
R76	Mg	12	Si, Ca	1120 mg/L	15 Amp	8	2	76	15	1140	7	10.7	0.55	0.74		230	-180	188.6	153.7	-18.5	1250	1015	-18.8

Silica Removal with IRON BLADES on REAL water (Control for Mg: R75 & R76)

| R77 | Fe | 12 | Si, Ca | 1120 mg/L | 8 Amp | 8 | 2 | 45 | 8 | 360 | 7 | 8.73 | 0.55 | 0.53 | | 230 | -183 | 188.6 | 174.2 | -7.6 | 1250 | 1040 | -16.8 |
| R78 | Fe | 12 | Si, Ca | 1120 mg/L | 15 Amp | 8 | 2 | 80 | 15 | 1200 | 7 | 9.77 | 0.55 | 0.27 | | 230 | -231 | 188.6 | 169.1 | -10.3 | 1250 | 1015 | -18.8 |

RESIDENCE TIME STUDY (w/ contaminate of moderate removal capacity)

RUN #	Blades	Base Solution	Contaminate(s)	Feed TDS	Special Condition	Pump Setting	Circuit Setup	Nominal Voltage	Nominal Amperage	Nominal Power	pH PRE	pH POST	NTU PRE	NTU POST	% Removal (Turbidity)	ORP PRE	ORP POST	Ca++ PRE	Ca++ POST	% Ca++ REMOVAL	Pre-TS (mg/L)	Post-TS (mg/L)	% CHANGE TS
R79	Fe	8	Al	874 mg/L	Lo Amp / Lo Flow	4	2	20	4	80	7	9.07	0.52	1.66		239	-207	88.9	77.1	-13.3	970	935	-3.6
R80	Fe	8	Al	874 mg/L	Med Amp / Med Flow	6	2	32	6	192	7	9.01	0.52	0.9		239	-166	88.9	73.8	-17.0	970	935	-3.6
R81	Fe	8	Al	874 mg/L	Hi Amp / Lo Flow	4	2	40	8	320	7	9.37	0.52	0.46		239	-192	88.9	45.1	-49.3	970	875	-9.8
R82	Fe	8	Al	874 mg/L	Hi Amp / Hi Flow	8	2	45	8	360	7	8.87	0.52	1.65		239	-170	88.9	75.8	-14.7	970	1005	3.6
R83	Fe	8	Al	874 mg/L	Lo Amp, Hi Flow	8	2	23	4	92	7	8.69	0.52	0.2		239	-205	88.9	82	-7.8	970	1005	3.6

BUREC ANTISCALANT STUDY

RUN #	Blades	Base Solution	Contaminate(s)	Feed TDS	Special Condition	Pump Setting	Circuit Setup	Nominal Voltage	Nominal Amperage	Nominal Power	pH PRE	pH POST	NTU PRE	NTU POST	% Removal (Turbidity)	ORP PRE	ORP POST	Ca++ PRE	Ca++ POST	% Ca++ REMOVAL	Pre-TS (mg/L)	Post-TS (mg/L)	% CHANGE TS
R84	Fe	8	Si (100 ppm), Ca	874 mg/L	8 Amp / 1-PASS	8	2	40	8	320	7.05	7.29	1.27	1.87		150	-159	38.9	36.5	-6.2	940	755	-19.7
R85	Fe	8	Si (100 ppm), Ca	874 mg/L	8 Amp / 2-PASS	8	2	34	8	272	7.05	9.27	1.27	0.22		150	-248	38.9	25.4	-34.7	940	955	1.6
R86	Fe	8	Si (100 ppm), Ca	874 mg/L	15 Amp / 1-PASS	8	2	73	15	1095	7.05	9.16	1.27	0.18		150	-247	38.9	27.9	-28.3	940	935	-0.5
R87	Fe	8	Si (100 ppm), Ca	874 mg/L	15 Amp / 2-PASS	8	2	53	15	795	7.05	10.02	1.27	0.12		150	-292	38.9	11.9	-69.4	940	980	4.3

Silica Removal with Mg Blades on Antiscalant Water

| R88 | Mg | 8 | Si (100 ppm), Ca | 874 mg/L | 8 Amp / 1-PASS | 8 | 2 | 36 | 8 | 288 | 7.05 | 10.41 | 1.27 | 2.65 | | 150 | -187 | 38.9 | 34.8 | -10.5 | 940 | 900 | -4.3 |
| R89 | Mg | 8 | Si (100 ppm), Ca | 874 mg/L | 8 Amp / 2-PASS | 8 | 2 | 30 | 8 | 240 | 7.05 | 10.7 | 1.27 | 0.21 | | 150 | -237 | 38.9 | 14.3 | -63.2 | 940 | 1060 | 12.8 |

INDIVIDUAL (Fe)

RUN #	Blades	Base Solution	Contaminate(s)	Feed TDS	Special Condition	Pump Setting	Circuit Setup	Nominal Voltage	Nominal Amperage	Nominal Power	pH PRE	pH POST	NTU PRE	NTU POST	% Removal (Turbidity)	ORP PRE	ORP POST	Ca++ PRE	Ca++ POST	% Ca++ REMOVAL	Pre-TS (mg/L)	Post-TS (mg/L)	% CHANGE TS
R90	Fe	8	Fe (10 ppm)	874 mg/L	8 Amp / 1-PASS	8	2	48	8	384	7	8.73	4.94	0.81		327	-175	111.6	82	-26.5	980	775	-20.9

INDIVIDUAL (Cs)

RUN #	Blades	Base Solution	Contaminate(s)	Feed TDS	Special Condition	Pump Setting	Circuit Setup	Nominal Voltage	Nominal Amperage	Nominal Power	pH PRE	pH POST	NTU PRE	NTU POST	% Removal (Turbidity)	ORP PRE	ORP POST	Ca++ PRE	Ca++ POST	% Ca++ REMOVAL	Pre-TS (mg/L)	Post-TS (mg/L)	% CHANGE TS
R91	Fe	8	Cs (10 ppm)	874 mg/L	8 Amp / 1-PASS	8	2	44	8	352	7.03	8.77	0.22	2.31		317	-205	---	---		860	900	4.7

INDIVIDUAL (Ag)

RUN #	Blades	Base Solution	Contaminate(s))	Feed TDS	Special Condition	Pump Setting	Circuit Setup	Nominal Voltage	Nominal Amperage	Nominal Power	pH PRE	pH POST	NTU PRE	NTU POST	% Removal (Turbidity)	ORP PRE	ORP POST	Ca++ PRE	Ca++ POST	% Ca++ REMOVAL	Pre-TS (mg/L)	Post-TS (mg/L)	% CHANGE TS
R92	Fe	8	Ag (< 10ppm)	874 mg/L	8 Amp / 1-PASS	8	2		8														#DIV/0!

PERCHLORATE, PHOSPHATE, NITRATE

RUN #	Blades	Base Solution	Contaminate(s))	Feed TDS	Special Condition	Pump Setting	Circuit Setup	Nominal Voltage	Nominal Amperage	Nominal Power	pH PRE	pH POST	NTU PRE	NTU POST	% Removal (Turbidity)	ORP PRE	ORP POST	Ca++ PRE	Ca++ POST	% Ca++ REMOVAL	Pre-TS (mg/L)	Post-TS (mg/L)	% CHANGE TS
R94	Fe	8	ClO4, PO4, NO3	874	8 Amp / 1-PASS	8	2	50	8	400	7.04	9.17	0.3	0.28		342	-225	72.1	65.6		1140	935	-18.0
R95	Fe	8	ClO4, PO4, NO3	874	15 Amp / 1-PASS	8	2	89	15	1335	7.04	9.32	0.3	0.21		342	-193	72.1	38.1		1140	1000	-12.3

HYDROCARBON CONDENSATE

RUN #	Blades	Base Solution	Contaminate(s))	Feed TDS	Special Condition	Pump Setting	Circuit Setup	Nominal Voltage	Nominal Amperage	Nominal Power	pH PRE	pH POST	NTU PRE	NTU POST	% Removal (Turbidity)	ORP PRE	ORP POST	Ca++ PRE	Ca++ POST	% Ca++ REMOVAL	Pre-TS (mg/L)	Post-TS (mg/L)	% CHANGE TS
R96	Al		carbon particulates			4	1	100	0.5	50	6		610	---	---	260							
R97	Al		carbon particulates		higher amperage	4	2	100	3.5	350	6		610	---	---	260							
R98	Al		carbon particulates		higher amperage	4	4	95	8.5	807.5	6		610	---	---	260							
R99	Al		carbon particulates		higher amperage	4	4	92	12.5	1150	6		610	0.38	99.94	260							
R100	Al		carbon particulates		higher amperage; lower pH	4	4	92	17.5	1610	4		610	---	---	260							
R101	Al		carbon particulates		lower amperage; lower pH	4	2	98	7	686	4		610	0.28	99.95	260							
R102	Al		carbon particulates		lower amperage; increased pH	4	1	100	2	200	5		610	1.84	99.70	260							

PESTICIDES*

RUN #	Blades	Base Solution	Contaminate(s))	Feed TDS	Special Condition	Pump Setting	Circuit Setup	Nominal Voltage	Nominal Amperage	Nominal Power	pH PRE	pH POST	NTU PRE	NTU POST	% Removal (Turbidity)	ORP PRE	ORP POST	Ca++ PRE	Ca++ POST	% Ca++ REMOVAL	Pre-TS (mg/L)	Post-TS (mg/L)	% CHANGE TS
R103	Fe	DI	DDT, Chlorpyrifos Lindane, Malathion			5			0.5		7												
R104	Fe	DI	DDT, Chlorpyrifos Lindane, Malathion		higher amperage	5			1		7												
R105	Fe	DI	DDT, Chlorpyrifos Lindane, Malathion		higher amperage	5			2.5		7												

* = runs conducted by an affiliate of Power Water Systems

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Table 4.2. Key to Tables 4.1 and 4.3

TABLE HEADING	EXPLANATION
Run #	from R1 through R90
Blades	blade material either iron, aluminum, or magnesium
Base Solution	see BASE SOLUTION KEY below
Contaminants	contaminants added to base solution; self explanatory
Feed TDS	(self explanatory)
Special Condition	Unique aspect of the run
Pump Setting	see PUMP SETTING KEY below
Circuit Setup	see CIRCUIT SETUP KEY below
Nominal Voltage	indicated voltage on power supply
Nominal Amperage	indicated amperage on power supply
Nominal Power	equals nominal voltage times nominal amperage
pH PRE	initial pH of feed solution
pH POST	pH after treatment
NTU PRE	turbidity of feed solution
NTU POST	turbidity of treated solution after filtering with 11 micron filter
% NTU REMOVAL	% turbidity removal based on NTU PRE and NTU POST values
ORP PRE	oxidation reduction potential of feed solution
ORP POST	oxidation reduction potential of treated solution
Ca++ PRE	calcium level (mg/L) in feed solution
Ca++ POST	calcium level (mg/L) in treated and filtered solution
% Ca++ REMOVAL	% calcium removal based on Ca++ PRE and Ca++ POST values
Pre-TS (mg/L)	total solids of feed solution
Post-TS (mg/L)	total solids of treated and filtered solution
% CHANGE TS	% change in TS based on Pre-TS and Post-TS values

BASE SOLUTION KEY

base solution #	makeup
1	2 g/L $CaCl_2*2H_2O$ + 3 g/L Na_2SO_4
2	25% of #1
3	50% of #1
4	#1 + 0.3 g/L $NaHCO_3$
5	#1 + NaOH + $NaHCO_3$
6	tap water
7	field sample - Oregon industrial waste
8	mock 1 (see separate listing)
9	1 g/L NaCl
10	NaCl to get conductivity of 1530
11	field sample - Red Tide
12	field samaple - cooling tower water
13	field sample - hydrocarbon condensate

mock 1 - solution defined as

mg/L	salt
15	KCl
158	$MgCl_2*6H_2O$
142	Na_2SO_4
338	$CaCl_2*2H_2O$
547	$NaHCO_3$

PUMP SETTING KEY

pump setting	flow (ml/min)
4	790
5	1000
6	1200
8	1665

CIRCUIT SETUP KEY　(9 metal blades)

	powered blades numbers	
circuit #	positive	negative
1	1	9
2	1, 9	5
3	1, 3, 5, 7, 9	2, 4, 6, 8
4	1, 5, 9	3, 7

Table 4.3. Tabulation of Removal Levels by Contaminant

LATEX PAINT

RUN #	Blades	Base Solution	Contaminate	Feed TDS	Other Contaminants Special Conditions	Pump Setting	Nominal Voltage	Nominal Amperage	Nominal Power	pH PRE	Conc. PRE	Conc. POST	% REMOVAL
R1	Al	1	latex paint			4	100	13	1300	6	494	0.4	99.92

OIL-WATER EMULSION

RUN #	Blades	Base Solution	Contaminate	Feed TDS	Other Contaminants Special Conditions	Pump Setting	Nominal Voltage	Nominal Amperage	Nominal Power	pH PRE	Conc. PRE	Conc. POST	% REMOVAL
R2	Al	1	100 ppm oil		+ 10ppm tannic & humic acid	4	100	13	1300	6	104	0.41	99.61
R4	Al	1	100 ppm oil			4	100	15.5	1550	6	34.7	0.59	98.30
R5	Al	1	100 ppm oil			4	100	15	1500	6	75.2	0.42	99.44
R6	Al	1	100 ppm oil			4	100	13	1300	6	69.9	0.27	99.61
R7	Al	1	200 ppm oil			4	100	13	1300	6	90.7	0.24	99.74
R8	Fe	1	100 ppm oil			4	90	18.5	1665	6	70.4	0.15	99.79
R9	Fe	1	100 ppm oil			8	100	15	1500	6	76	0.42	99.45
R10	Fe	1	100 ppm oil	~4,000	higher salinity	8	50	9	450	6	88.6	0.25	99.72
R11	Fe	2	100 ppm oil	~1,000	lower salinity	8	50	3	150	6	56.7	0.13	99.77
R12	Fe	3	100 ppm oil	~2,000	medium salinity	8	50	5	250	6	89.6	0.15	99.83
R13	Fe	1	100 ppm oil		lower power	8	25	4	100	6	73.3	0.16	99.78
R14	Fe	1	100 ppm oil		lower power	8	5	0.9	4.5	6	42.2	0.11	99.74
R15	Fe	1	100 ppm oil		higher oil content	8	5	0.75	3.75	6	208	0.15	99.93
R16	Fe	4	100 ppm oil		+0.3g/L NaHCO3	8	5	0.7	3.5	6.5	51.2	0.17	99.67
R17	Fe	5	100 ppm oil		+0.3g/L NaHCO3; low temperature	8	5	0.75	3.75	8.06	127	0.33	99.74
R18	Fe	4	100 ppm oil		+0.3g/L NaHCO3	8	5	0.6	3	7.92	74.6	0.34	99.54
R19	Fe	6	100 ppm oil			8	100	0.4	40	7.88	136	0.2	99.85
R20	Fe	6	100 ppm oil		high temperature	8	100	0.4	40	7.99	132	0.12	99.91
R21	Fe	1	100 ppm oil		high flow	2x '8'	5	0.6	3	6.3	64.7	0.19	99.71
R22	Fe	1	100 ppm oil		high flow	2x '8'	5	0.4	2	6.34	68.4	0.31	99.55

TANNIC / HUMIC ACID

RUN #	Blades	Base Solution	Contaminate	Feed TDS	Other Contaminants Special Conditions	Pump Setting	Nominal Voltage	Nominal Amperage	Nominal Power	pH PRE	Conc. PRE	Conc. POST	% REMOVAL
R2	Al	1	10 ppm tannic & humic acid		100 ppm oil	4	100	15.5	1550	6	34.7	0.59	98.30
R3	Al	1	same			4	100	15	1500	6	5.47	0.66	87.93
R25	Fe	1	same			4	90	14	1260	7.91	5.07	0.34	93.29

SILT

RUN #	Blades	Base Solution	Contaminate	Feed TDS	Other Contaminants Special Conditions	Pump Setting	Nominal Voltage	Nominal Amperage	Nominal Power	pH PRE	Conc. PRE	Conc. POST	% REMOVAL
R23	Fe	1				8	5	1	5	8.14	612	0.3	99.95
R24	Fe	4			+0.3g/L NaHCO3; pH 11.11	8	5	1	5	11.11	117	0.42	99.64

ARSENIC / SILICA

RUN #	Blades	Base Solution	Contaminate	Feed TDS	Other Contaminants Special Conditions	Pump Setting	Nominal Voltage	Nominal Amperage	Nominal Power	pH PRE	Conc. PRE	Conc. POST	% REMOVAL
R26	Fe	7	As		Oregon sample	8	100	0.6	60	3.33	219	148	32.42

RUN #	Blades	Base Solution	Contaminate	Feed TDS	Other Contaminants / Special Conditions	Pump Setting	Nominal Voltage	Nominal Amperage	Nominal Power	pH PRE	Conc. PRE	Conc. POST	% REMOVAL
R26	Fe	7	Si		Oregon sample	8	100	0.6	60	3.33	37	37	**0.00**
R27	Fe	7	As		Oregon sample; high amp	8	25	7	175	7.64	---	---	**---**
R27	Fe	7	Si		Oregon sample; high amp	8	25	7	175	7.64	---	---	**---**
R28	Fe	7	As		Oregon sample; low amp	8	5	1	5	7.74	---	---	**---**
R28	Fe	7	Si		Oregon sample; low amp	8	5	1	5	7.74	---	---	**---**
R29	Fe	8	As		low amp; mock solution	8	27	1	27	9.33	6.6	5	**24.24**
R29	Fe	8	Si		low amp; mock solution	8	27	1	27	9.33	50	37	**26.00**
R30	Fe	8	As		high amp; mock solution	8	98	4	392	9.33	6.6	0.14	**97.88**
R30	Fe	8	Si		high amp; mock solution	8	98	4	392	9.33	50	1.1	**97.80**
R34	Fe	8	As		mock solution	8	42	10	420	7.07	6.1	0.028	**99.54**
R34	Fe	8	Si		mock solution	8	42	10	420	7.07	53	1.2	**97.74**
R35	Fe	8	As		+NaCl; mock solution	8	24	10	240	7.68	7.1	0.05	**99.30**
R35	Fe	8	Si		+NaCl; mock solution	8	24	10	240	7.68	51	1.3	**97.45**
R36	Fe	7	As		Oregon sample; med. power.	8	12	10	120	3.27	212	85	**59.91**
R36	Fe	7	Si		Oregon sample; med. power.	8	12	10	120	3.27	35	34	**2.86**
R37	Fe	7	As		Oregon sample; high power	8	24	17.5	420	3.27	212	44	**79.25**
R37	Fe	7	Si		Oregon sample; high power	8	24	17.5	420	3.27	35	33	**5.71**
R54	Fe	7	As		Oregon sample; 1 pass	8	98	3.5	343	3.03	198	69.2	**65.05**
R54	Fe	7	Si		Oregon sample; 1 pass	8	98	3.5	343	3.03	32	31	**3.13**
R55	Fe	7	As		Oregon sample; 2nd pass	8	98	2	196	3.03	198	28.7	**85.51**
R55	Fe	7	Si		Oregon sample; 2nd pass	8	98	2	196	3.03	32	24	**25.00**
R56	Fe	7	As		Oregon sample; 1 pass	8	12	10	120	3.03	198	98	**50.51**
R56	Fe	7	Si		Oregon sample; 1 pass	8	12	10	120	3.03	32	32	**0.00**
R57	Fe	7	As		Oregon sample; 2nd pass	8	16	10	160	3.03	198	27.6	**86.06**
R57	Fe	7	Si		Oregon sample; 2nd pass	8	16	10	160	3.03	32	29	**9.38**

CALCIUM

RUN #	Blades	Base Solution	Contaminate	Feed TDS	Other Contaminants / Special Conditions	Pump Setting	Nominal Voltage	Nominal Amperage	Nominal Power	pH PRE	Conc. PRE	Conc. POST	% REMOVAL
R5	Al	1	Ca		100 ppm oil	4	100	13	1300	6	463	328	**29.16**
R7	Al	1	Ca		100 ppm oil	4	100	13	1300	6	463	310	**33.05**
R8	Fe	1	Ca		100 ppm oil	4	90	18.5	1665	6	463	451	**2.59**
R10	Fe	1	Ca	~ 4,000	100 ppm oil; higher salinity	8	50	9	450	6	463	488	**0**
R11	Fe	2	Ca		100 ppm oil; low salinity	8	50	3	150	6	116	122	**0**
R12	Fe	3	Ca		100 ppm oil; medium salinity	8	50	5	250	6	232	255	**0**
R13	Fe	1	Ca		100 ppm oil; low power	8	25	4	100	6	463	517	**0**
R14	Fe	1	Ca		100 ppm oil; very low power	8	5	0.9	4.5	6	463	529	**0**
R15	Fe	1	Ca		200 ppm oil	8	5	0.75	3.75	6	463	547	**0**
R16	Fe	4	Ca		100 ppm oil; +0.3g/L NaHCO3	8	5	0.7	3.5	6.5	463	506	**0**
R17	Fe	5	Ca		100 ppm oil; +0.3g/L NaHCO3, low temp.	8	5	0.75	3.75	8.1	463	435	**6.05**
R21	Fe	1	Ca		100 ppm oil; high flow	2x 8	5	0.6	3	6.3	463	514	**0**
R22	Al	1	Ca		100 ppm oil; low flow	2x 8	5	0.4	2	6.3	463	537	**0**
R23	Fe	1	Ca		silt mixture	8	5	1	5	8.1	463	537	**0**
R24	Fe	4	Ca		silt mixture; + 0.3g/L NaHCO3; high pH	8	5	1	5	11	463	373	**19.44**
R58	Fe	8	Ca	874	metal soup; 1 pass	8	56	8	448	6.92	58.2	45.9	**21.13**
R59	Fe	8	Ca	874	metal soup; 2nd pass	8	58	8	464	6.92	58.2	16.4	**71.82**
R60	Fe	8	Ca	874	Sr, Cr	8	52	8	416	7.04	85.7	57.4	**33.02**
R61	Fe	8	Ca	874	Sr, Cr	8	52	8	416	7	85.7	36.9	**56.94**
R62	Fe	8	Ca	874	Sr, Cr	8	52	8	416	7	85.6	10.2	**88.08**

RUN #	Blades	Base Solution	Contaminate	Feed TDS	Other Contaminants Special Conditions	Pump Setting	Nominal Voltage	Nominal Amperage	Nominal Power	pH PRE	Conc. PRE	Conc. POST	% REMOVAL
R63	Fe	8	Ca	874	Cr	8	52	8	416	6.97	---	65.7	---
R64	Fe	8	Ca	35,000	Cr, high salinity	8	<1	8	< 8	6.95	---	75.4	---
R65	Fe	8	Ca	874	Ba	8	45	8	360	6.93	66	45.1	31.67
R66	Fe	8	Ca	874	Cd	8	50	8	400	7.07	67.2	52.1	22.47
R67	Fe	8	Ca	874	Sr, Cr	8	46	8	368	7	73	63.5	13.01
R68	Fe	8	Ca	35,000	Sr, high salinity	8	<1	8	<8	7	81.2	32.8	59.61
R69	Mg	8	Ca	874	Si; Mg blade; 8 amp; high pH	8	40	8	320	10.95	30.7	3.3	89.25
R70	Mg	8	Ca	874	Si; Mg blade; 15 amp; high pH	8	71	15	1065	10.95	30.7	3.7	87.95
R71	Mg	8	Ca	874	Si; Mg blade; 8 amp; neutral pH	8	39	8	312	8.65	27.2	4.1	84.93
R72	Mg	8	Ca	874	Si; Mg blade; 15 amp; neutral pH	8	70	15	1050	8.65	27.2	4.1	84.93
R73	Fe	8	Ca	874	Si; 8 amp; neutral pH	8	43	8	344	8.65	27.2	12.7	53.31
R74	Fe	8	Ca	874	Si; 15 amp neutral pH	8	76	15	1140	8.65	27.2	9.4	65.44
R75	Mg	12	Ca	1,120	Si; Mg blade; 8 amp	8	40	8	320	7	188.6	155.8	17.39
R76	Mg	12	Ca	1,120	Si; Mg blade; 15 amp	8	76	15	1140	7	188.6	153.7	18.50
R77	Fe	12	Ca	1,120	Si; 8 amp	8	45	8	360	7	188.6	174.2	7.64
R78	Fe	12	Ca	1,120	Si; 15 amp	8	80	15	1200	7	188.6	169.1	10.34
R79	Fe	8	Ca	874	Al; low amp; low flow	4	20	4	80	7	88.9	77.1	13.27
R80	Fe	8	Ca	874	Al; medium amp; medium flow	6	32	6	192	7	88.9	73.8	16.99
R81	Fe	8	Ca	874	Al; high amp; low flow	4	40	8	320	7	88.9	45.1	49.27
R82	Fe	8	Ca	874	Al; high amp; high flow	8	45	8	360	7	88.9	75.8	14.74
R83	Fe	8	Ca	874	Al; low amp; high flow	8	23	4	92	7	88.9	82	7.76
R84	Fe	8	Ca	874	Si; 1 pass	8	40	8	320	7.06	38.9	36.5	6.17
R85	Fe	8	Ca	874	Si; 2nd pass	8	34	8	272	7.05	38.9	25.4	34.70
R86	Fe	8	Ca	874	Si; higher amp; 1 pass	8	73	15	1095	7.05	38.9	27.9	28.28
R87	Fe	8	Ca	874	Si; higher amp; 2nd pass	8	53	15	795	7.05	38.9	11.9	69.41
R88	Mg	8	Ca	874	Si; Mg blade; 1 pass	8	36	8	288	7.05	38.9	34.8	10.54
R89	Mg	8	Ca	874	Si; Mg blade; 2nd pass	8	30	8	240	7.05	38.9	14.3	63.24
R90	Fe	8	Ca	874	Fe	8	48	8	384	7	105	80	23.81
R94	Fe	8	Ca	874	ClO4, PO4, NO3	8	50	8	400	7.04	72.1	65.6	9.02
R95	Fe	8	Ca	874	ClO4, PO4, NO3; higher amp	8	89	15	1335	7.04	72.1	38.1	47.16

METAL SOUP

RUN #	Blades	Base Solution	Contaminate	Feed TDS	Other Contaminants Special Conditions	Pump Setting	Nominal Voltage	Nominal Amperage	Nominal Power	pH PRE	Conc. PRE	Conc. POST	% REMOVAL
R38	Fe	8	Al		pH 7; medium power; metal soup	8	52	8	416	6.98	0.65	0.28	56.92
R38	Fe	8	As		pH 7; medium power; metal soup	8	52	8	416	6.98	2.1	<0.2	>99.05
R38	Fe	8	Ba		pH 7; medium power; metal soup	8	52	8	416	6.98	0.4	0.28	30.00
R38	Fe	8	Cd		pH 7; medium power; metal soup	8	52	8	416	6.98	2.3	<0.01	>99.57
R38	Fe	8	Cs		pH 7; medium power; metal soup	8	52	8	416	6.98	11	10	9.09
R38	Fe	8	Cr		pH 7; medium power; metal soup	8	52	8	416	6.98	10	<0.05	>99.50
R38	Fe	8	Cu		pH 7; medium power; metal soup	8	52	8	416	6.98	0.63	<0.05	>92.06
R38	Fe	8	Fe		pH 7; medium power; metal soup	8	52	8	416	6.98	0.67	<0.05	>92.54
R38	Fe	8	Si		pH 7; medium power; metal soup	8	52	8	416	6.98	7.1	0.91	87.18
R38	Fe	8	Sr		pH 7; medium power; metal soup	8	52	8	416	6.98	7.2	6	16.67
R38	Fe	8	Zn		pH 7; medium power; metal soup	8	52	8	416	6.98	2.2	<0.05	>97.73
R39	Fe	8	Al		pH 8, low power; metal soup	8	4	1	4	8.12	0.36	0.32	11.11
R39	Fe	8	As		pH 8, low power; metal soup	8	4	1	4	8.12	2	1.1	45.00
R39	Fe	8	Ba		pH 8, low power; metal soup	8	4	1	4	8.12	0.23	0.23	0.00
R39	Fe	8	Cd		pH 8, low power; metal soup	8	4	1	4	8.12	1	<0.01	>99.00

RUN #	Blades	Base Solution	Contaminate	Feed TDS	Other Contaminants / Special Conditions	Pump Setting	Nominal Voltage	Nominal Amperage	Nominal Power	pH PRE	Conc. PRE	Conc. POST	% REMOVAL
R39	Fe	8	Cs		pH 8, low power; metal soup	8	4	1	4	8.12	11	11	**0.00**
R39	Fe	8	Cr		pH 8, low power; metal soup	8	4	1	4	8.12	10	0.45	**95.50**
R39	Fe	8	Cu		pH 8, low power; metal soup	8	4	1	4	8.12	0.33	<0.05	**>84.85**
R39	Fe	8	Fe		pH 8, low power; metal soup	8	4	1	4	8.12	0.3	<0.05	**>83.33**
R39	Fe	8	Si		pH 8, low power; metal soup	8	4	1	4	8.12	6.4	4.3	**32.81**
R39	Fe	8	Sr		pH 8, low power; metal soup	8	4	1	4	8.12	7	6.1	**12.86**
R39	Fe	8	Zn		pH 8, low power; metal soup	8	4	1	4	8.12	0.8	<0.05	**>93.75**
R40	Fe	8	Al		pH 8; high power; metal soup	8	90	15	1350	8.12	0.36	0.44	**-22.22**
R40	Fe	8	As		pH 8; high power; metal soup	8	90	15	1350	8.12	2	<0.2	**>90.00**
R40	Fe	8	Ba		pH 8; high power; metal soup	8	90	15	1350	8.12	0.23	0.24	**-4.35**
R40	Fe	8	Cd		pH 8; high power; metal soup	8	90	15	1350	8.12	1	<0.01	**>99.00**
R40	Fe	8	Cs		pH 8; high power; metal soup	8	90	15	1350	8.12	11	10	**9.09**
R40	Fe	8	Cr		pH 8; high power; metal soup	8	90	15	1350	8.12	10	<0.05	**>99.50**
R40	Fe	8	Cu		pH 8; high power; metal soup	8	90	15	1350	8.12	0.33	<0.05	**>84.85**
R40	Fe	8	Fe		pH 8; high power; metal soup	8	90	15	1350	8.12	0.3	<0.05	**>83.33**
R40	Fe	8	Si		pH 8; high power; metal soup	8	90	15	1350	8.12	6.4	0.98	**84.69**
R40	Fe	8	Sr		pH 8; high power; metal soup	8	90	15	1350	8.12	7	5	**28.57**
R40	Fe	8	Zn		pH 8; high power; metal soup	8	90	15	1350	8.12	0.8	<0.05	**>93.75**
R41	Fe	8	Al		pH 6; low power; metal soup	8	5	1	5	6.04	0.07	<0.05	**>28.57**
R41	Fe	8	As		pH 6; low power; metal soup	8	5	1	5	6.04	0.8	<0.2	**>75.00**
R41	Fe	8	Ba		pH 6; low power; metal soup	8	5	1	5	6.04	0.13	0.24	**-84.62**
R41	Fe	8	Cd		pH 6; low power; metal soup	8	5	1	5	6.04	5.7	3.9	**31.58**
R41	Fe	8	Cs		pH 6; low power; metal soup	8	5	1	5	6.04	11	11	**0.00**
R41	Fe	8	Cr		pH 6; low power; metal soup	8	5	1	5	6.04	10	1.2	**88.00**
R41	Fe	8	Cu		pH 6; low power; metal soup	8	5	1	5	6.04	1.5	<0.05	**>96.67**
R41	Fe	8	Fe		pH 6; low power; metal soup	8	5	1	5	6.04	<0.05	<0.05	**---**
R41	Fe	8	Si		pH 6; low power; metal soup	8	5	1	5	6.04	8.3	7.2	**13.25**
R41	Fe	8	Sr		pH 6; low power; metal soup	8	5	1	5	6.04	7.2	7.1	**1.39**
R41	Fe	8	Zn		pH 6; low power; metal soup	8	5	1	5	6.04	11	5	**54.55**
R42	Fe	8	Al		pH 6; high power; metal soup	8	90	15	1350	6.04	0.07	<0.05	**>28.57**
R42	Fe	8	As		pH 6; high power; metal soup	8	90	15	1350	6.04	0.8	<0.2	**>75.00**
R42	Fe	8	Ba		pH 6; high power; metal soup	8	90	15	1350	6.04	0.13	0.33	**-153.85**
R42	Fe	8	Cd		pH 6; high power; metal soup	8	90	15	1350	6.04	5.7	0.05	**99.12**
R42	Fe	8	Cs		pH 6; high power; metal soup	8	90	15	1350	6.04	11	11	**0.00**
R42	Fe	8	Cr		pH 6; high power; metal soup	8	90	15	1350	6.04	10	<0.05	**>99.50**
R42	Fe	8	Cu		pH 6; high power; metal soup	8	90	15	1350	6.04	1.5	<0.05	**>96.67**
R42	Fe	8	Fe		pH 6; high power; metal soup	8	90	15	1350	6.04	<0.05	0.08	**---**
R42	Fe	8	Si		pH 6; high power; metal soup	8	90	15	1350	6.04	8.3	1.3	**84.34**
R42	Fe	8	Sr		pH 6; high power; metal soup	8	90	15	1350	6.04	7.2	7.1	**1.39**
R42	Fe	8	Zn		pH 6; high power; metal soup	8	90	15	1350	6.04	11	<0.05	**>99.55**

RADIONUCLIDES

RUN #	Blades	Base Solution	Contaminate	Feed TDS	Other Contaminants / Special Conditions	Pump Setting	Nominal Voltage	Nominal Amperage	Nominal Power	pH PRE	Conc. PRE	Conc. POST	% REMOVAL
R43	Fe	8	Sr	1,000	pH 6; low power; Cs, I	8	2	1	2	6.06	0.223	0.003	**98.65**
R43	Fe	8	Cs	1,000	pH 6; low power; I, Sr	8	2	1	2	6.06	0.15	0.13	**13.33**
R43	Fe	8	I	1,000	pH 6; low power; Sr, Cs	8	2	1	2	6.06	0.012	0.036	**---**
R44	Fe	8	Sr	1,000	pH 6; high power; Cs, I	8	50	15	750	6.06	0.223	0.059	**73.54**
R44	Fe	8	Cs	1,000	pH 6; high power; I, Sr	8	50	15	750	6.06	0.15	0.13	**13.33**

RUN #	Blades	Base Solution	Contaminate	Feed TDS	Other Contaminants Special Conditions	Pump Setting	Nominal Voltage	Nominal Amperage	Nominal Power	pH PRE	Conc. PRE	Conc. POST	% REMOVAL
R44	Fe	8	I	1,000	pH 6; high power; Sr, Cs	8	50	15	750	6.06	0.012	0.011	**8.33**
R45	Fe	8	Sr	1,000	pH 8; low power; Cs, I	8	2	1	2	8.1	0.223	0.002	**99.10**
R45	Fe	8	Cs	1,000	pH 8; low power; I, Sr	8	2	1	2	8.1	0.15	0.13	**13.33**
R45	Fe	8	I	1,000	pH 8; low power; Sr, Cs	8	2	1	2	8.1	0.012	0.011	**8.33**
R46	Fe	8	Sr	1,000	pH 8; high power; Cs, I	8	50	15	750	8.1	0.223	0.019	**91.48**
R46	Fe	8	Cs	1,000	pH 8; high power; I, Sr	8	50	15	750	8.1	0.15	0.13	**13.33**
R46	Fe	8	I	1,000	pH 8; high power; Sr, Cs	8	50	15	750	8.1	0.012	<0.001	**>91.67**

Sr, Cr, Ba SINGLE AND DOUBLE PASS

RUN #	Blades	Base Solution	Contaminate	Feed TDS	Other Contaminants Special Conditions	Pump Setting	Nominal Voltage	Nominal Amperage	Nominal Power	pH PRE	Conc. PRE	Conc. POST	% REMOVAL
R58	Fe	8	Sr	874	1 pass	8	56	8	448	6.92	6.9	6	**13.04**
R58	Fe	8	Cr	874	1 pass	8	56	8	448	6.92	8.1	<0.02	**>99.75**
R58	Fe	8	Ba	874	1 pass	8	56	8	448	6.92	0.29	0.33	**0.00**
R59	Fe	8	Sr	874	2nd pass	8	52	8	416	6.92	6.9	5.8	**15.94**
R59	Fe	8	Cr	874	2nd pass	8	52	8	416	6.92	8.1	<0.02	**>99.75**
R59	Fe	8	Ba	874	2nd pass	8	52	8	416	6.92	0.29	0.28	**3.45**

Sr:Cr RATIO

RUN #	Blades	Base Solution	Contaminate	Feed TDS	Other Contaminants Special Conditions	Pump Setting	Nominal Voltage	Nominal Amperage	Nominal Power	pH PRE	Conc. PRE	Conc. POST	% REMOVAL
R60	Fe	8	Sr	874	10:1 ratio	8	52	8	416	7.04	79	77	**2.53**
R60	Fe	8	Cr	874	10:1 ratio	8	52	8	416	7.04	9.3	<0.02	**>99.78**
R61	Fe	8	Sr	874	5:5 ratio	8	52	8	416	7	39	2.4	**93.85**
R61	Fe	8	Cr	874	5:5 ratio	8	52	8	416	7	58	<0.02	**>99.97**
R62	Fe	8	Sr	874	1:10 ratio	8	52	8	416	7	8	1.1	**86.25**
R62	Fe	8	Cr	874	1:10 ratio	8	52	8	416	7	110	4.8	**95.64**

INDIVIDUAL METALS

RUN #	Blades	Base Solution	Contaminate	Feed TDS	Other Contaminants Special Conditions	Pump Setting	Nominal Voltage	Nominal Amperage	Nominal Power	pH PRE	Conc. PRE	Conc. POST	% REMOVAL
R63	Fe	8	Cr	874		8	52	8	416	6.97	9.2	<0.02	**>99.78**
R64	Fe	8	Cr	35,000	high salinity	8	<1	8	<8	6.95	9.2	<0.02	**>99.78**
R65	Fe	8	Ba	874		8	45	8	360	6.93	0.23	0.26	**0.00**
R66	Fe	8	Cd	874		8	50	8	400	7.07	9.5	<0.6	**>93.68**
R67	Fe	8	Sr	874		8	48	8	384	7	8.5	7.7	**9.41**
R68	Fe	8	Sr	35,000	high salinity	8	<1	8	<8	7	8.5	6.4	**24.71**
R90	Fe	8	Fe	874		8	48	8	384	7	---	---	**---**
R90	Fe	8	Na	874		8	48	8	384	7	170	170	**0.00**
R90	Fe	8	Mg	874		8	48	8	384	7	16	13.2	**17.50**
R90	Fe	8	Mn	874		8	48	8	384	7	0.038	0.052	**0.00**
R91	Fe	8	Cs	874		8	44	8	352	7.03	13	13	**0.00**
R92	Fe	8	Ag	874		8	44	8	352	7	0.098	<0.010	**>89.80**

SILICA

RUN #	Blades	Base Solution	Contaminate	Feed TDS	Other Contaminants Special Conditions	Pump Setting	Nominal Voltage	Nominal Amperage	Nominal Power	pH PRE	Conc. PRE	Conc. POST	% REMOVAL
R69	Mg	8	Si	874	8 amp; high pH	8	40	8	320	10.95	94	13	**86.17**
R70	Mg	8	Si	874	15 amp; high pH	8	71	15	1065	10.95	94	---	**---**

RUN #	Blades	Base Solution	Contaminate	Feed TDS	Other Contaminants Special Conditions	Pump Setting	Nominal Voltage	Nominal Amperage	Nominal Power	pH PRE	Conc. PRE	Conc. POST	% REMOVAL
R71	Mg	8	Si	874	8 amp; neutral pH	8	39	8	312	8.65	93	10	**89.25**
R72	Mg	8	Si	874	15 amp; neutral pH	8	70	15	1050	8.65	93	2	**97.85**
R73	Fe	8	Si	874	8 amp; neutral pH	8	43	8	344	8.65	93	3.7	**96.02**
R74	Fe	8	Si	874	15 amp; neutral pH	8	76	15	1140	8.65	93	0.48	**99.48**
R75	Mg	12	Si	1,120	8 amp	8	40	8	320	7	66	3.9	**94.09**
R76	Mg	12	Si	1,120	15 amp	8	76	15	1140	7	66	2.9	**95.61**
R77	Fe	12	Si	1,120	8 amp	8	45	8	360	7	66	9.8	**85.15**
R78	Fe	12	Si	1,120	15 amp	8	80	15	1200	7	66	0.44	**99.33**
R84	Fe	8	Si	874	8 amp; 1 pass	8	40	8	320	7.06	84	10	**88.10**
R85	Fe	8	Si	874	8 amp; 2nd pass	8	34	8	272	7.05	84	0.51	**99.39**
R86	Fe	8	Si	874	15 amp; 1 pass	8	73	15	1095	7.05	84	0.38	**99.55**
R87	Fe	8	Si	874	15 amp; 2nd pass	8	53	15	795	7.05	84	0.13	**99.85**
R88	Mg	8	Si	874	8 amp; 1 pass	8	36	8	288	7.05	84	9.3	**88.93**
R89	Mg	8	Si	874	8 amp; 2nd pass	8	30	8	240	7.05	84	1.7	**97.98**

ALUMINUM & RESIDENCE TIME

RUN #	Blades	Base Solution	Contaminate	Feed TDS	Other Contaminants Special Conditions	Pump Setting	Nominal Voltage	Nominal Amperage	Nominal Power	pH PRE	Conc. PRE	Conc. POST	% REMOVAL
R79	Fe	8	Al	874	4 amp; low flow	4	20	4	80	7	0.41	0.093	**77.32**
R80	Fe	8	Al	874	6 amp; medium flow	6	32	6	192	7	0.41	<0.05	**>87.80**
R81	Fe	8	Al	874	8 amp; low flow	4	40	8	320	7	0.41	0.33	**19.51**
R82	Fe	8	Al	874	8 amp; high flow	8	45	8	360	7	0.41	0.16	**60.98**
R83	Fe	8	Al	874	4 amp; high flow	4	23	4	92	7	0.41	0.096	**76.59**

PERCHLORATE, PHOSPHATE, & NITRATE

RUN #	Blades	Base Solution	Contaminate	Feed TDS	Other Contaminants Special Conditions	Pump Setting	Nominal Voltage	Nominal Amperage	Nominal Power	pH PRE	Conc. PRE	Conc. POST	% REMOVAL
R94	Fe	8	ClO4	874	8 amp	8	50	8	400	7.04	23.7	19.6	**17.30**
R94	Fe	8	PO4	874	8 amp	8	50	8	400	7.04	5.21	<0.20	**>96.16**
R94	Fe	8	NO3	874	8 amp	8	50	8	400	7.04	6.07	5.66	**6.75**
R95	Fe	8	ClO4	874	15 amp	8	89	15	1335	7.04	23.7	21.1	**10.97**
R95	Fe	8	PO4	874	15 amp	8	89	15	1335	7.04	5.21	<0.20	**>96.16**
R95	Fe	8	NO3	874	15 amp	8	89	15	1335	7.04	6.07	5.98	**1.48**

HYDROCARBON CONDENSATE

RUN #	Blades	Base Solution	Contaminate	Feed TDS	Other Contaminants Special Conditions	Pump Setting	Nominal Voltage	Nominal Amperage	Nominal Power	pH PRE	Conc. PRE (NTU)	Conc. POST	% REMOVAL
R96	Al	real water	carbon particulates		nonvisible sign of coagulation	4	100	0.5	50	6	610	---	**---**
R97	Al	real water	carbon particulates		minor coagulation	4	100	3.5	350	6	610	---	**---**
R98	Al	real water	carbon particulates		visible settling after treatment	4	95	8.5	807.5	6	610	---	**---**
R99	Al	real water	carbon particulates		good settling / separation	4	92	12.5	1150	6	610	0.38	**99.94**
R100	Al	real water	carbon particulates		good settling / separation	4	92	17.5	1610	4	610	---	**---**
R101	Al	real water	carbon particulates		good settling / separation	4	98	7	686	4	610	0.28	**99.95**
R102	Al	real water	carbon particulates		good settling / separation	4	100	2	200	5	610	1.84	**99.70**

PESTICIDES*

RUN #	Blades	Base Solution	Contaminate	Feed TDS	Other Contaminants Special Conditions	Pump Setting	Nominal Voltage	Nominal Amperage	Nominal Power	pH PRE	Conc. PRE	Conc. POST	% REMOVAL
R103		DI water	DDT	---	0.5 amp	5	---	0.5	---	7	0.016	0.0026	**83.75**

R103		DI water	Chlorpyrifos	---	0.5 amp	5	---	0.5	---	7	0.04	0.028	**30.00**
R103		DI water	Lindane	---	0.5 amp	5	---	0.5	---	7	0.079	0.042	**46.84**
R103		DI water	Malathion	---	0.5 amp	5	---	0.5	---	7	0.081	0.0033	**95.93**
R104		DI water	DDT	---	1.0 amp	5	---	1	---	7	0.016	0.0021	**86.88**
R104		DI water	Chlorpyrifos	---	1.0 amp	5	---	1	---	7	0.04	0.027	**32.50**
R104		DI water	Lindane	---	1.0 amp	5	---	1	---	7	0.079	0.04	**49.37**
R104		DI water	Malathion	---	1.0 amp	5	---	1	---	7	0.081	0.051	**37.04**
R105		DI water	DDT	---	2.5 amp	5	---	2.5	---	7	0.016	0.0003	**98.13**
R105		DI water	Chlorpyrifos	---	2.5 amp	5	---	2.5	---	7	0.04	0.0038	**90.50**
R105		DI water	Lindane	---	2.5 amp	5	---	2.5	---	7	0.079	0.00076	**99.04**
R105		DI water	Malathion	---	2.5 amp	5	---	2.5	---	7	0.081	ND	**>99.00**

* = runs conducted by an affiliate of Powell Water Systems

R4) were obtained at all power levels.   With such high removal levels in all runs it is difficult to determine the influence of system variables on removal results.

The removal levels were not obviously affected by blade material. Aluminum blades were used in runs R2, and R4 - R7. Iron blades were used in the other runs.

The effect of salinity (over the range of 1,000 to 4,000 mg/L) in runs R10 to R12 showed no obvious effect on removal.   The effect of salinity on conductivity, however, is shown by the increased amperage attained at the constant 50 volt level used in these three runs.

The higher oil content (200 ppm as opposed to 100 ppm) of run R15 gave the highest removal level attained in these runs (99.93%). Neither the addition of NaHCO3 to introduce carbonate species (Runs R16 – R18) nor the varying of temperature (8C, 22.7C, and 50C) in runs R18 to R20 had any obvious effect on removal levels.

Similarly, increasing the flow (decreasing the residence time) in runs R21 and R22 did not have any measurable effect on removal levels.

The effect of the background chemical matrix, where the six different base solutions were used, did not appear to have any effect on removal.

Material balances were studied during the oil-water emulsion runs.   These were done in terms of total solids determinations at various steps during the treatment process. The determinations included:

- Total solids of feed solution (A)

The total solids of the feed solution include both total dissolved and suspended solids.

- Total solids of treated solution (B)

The EC treatment introduces some of the electrode material into the solution and there are subsequent chemical reactions, including oxidation and reduction reactions, which modify

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species in solution.   For example, metals may be converted into various oxy-hydroxy complexes in which case the mass of the metal solids (now metal complexes) will increase due to the bound oxygen and hydroxyl groups.   As a result, the total solids of the treated solution includes the original total solids, the mass added from the electrodes, and any mass changes due to oxidation and other chemical reactions.

- Total solids for treated and filtered (11 micron) solution (C)

Filtration of the treated solution removes those species that are large enough to be removed by the gravity filtration step.   This includes solids and material adsorbed or complexed onto these solids.

The difference between B and A reflects the increase in the amount of solids due to treatment. In early runs (R1 through R10) the total solids of the treated solution (B) was considerably greater (by 20 to 80%) than the total solids of the feed.   As the amperage was decreased in following runs (such as R14 through R24) the total solids of the treated solution (B) more closely resembled the total solids of the feed (A).   As can be seen in Table 4.3, the removal of suspended solids did not decrease with decreasing amperage.

A reasonable interpretation is that the high amperage runs 'overpowered' the system in supplying more power (amperage) than necessary to accomplish the high removal levels. This excess energy gave rise to visibly darker solutions and higher floc levels due to the excessive dissolution of the electrodes.

C represents the total solids of the filtered and treated solution.   It is equal to B minus that solids not passing through the 11 micron filter.   Reasons for C to be less than A include: removal of suspended solids from the feed and possible removal of some originally dissolved solids from the feed.   Reasons for C to be greater than A include: presence of solids created during treatment that pass through the 11 micron filter.

In early runs an attempt was made to determine how much of the electrode material was lost during a run.   The blades were weighed before and after treatment.   This proved not to be a useful measurement. The testing protocol called for cleaning of the blades following a run to remove any oxide or surface buildup and to assure the same starting conditions at the beginning of each run. While such cleaning is not necessary in field use it was done to establish reproducible run conditions as much as possible.   The blade loss from cleaning was shown to be considerably more than any blade loss from blade use.

4.1.1.3 Tannic and Humic Acid Mixture – Mock Solutions: Three runs (R2, R3 and R25) were made with 10 ppm each of humic and tannic acid. Removal levels were not as high as with the other suspended solids runs and likely due to a broader range of or general smaller solid size of the tannic and humic acids in the feed solution – relative to the other suspended solids solutions.   The removal levels in runs R3 and R25 were 87.93 and 93.29 percent. The higher removal level of R25 might be due to the use of the iron blades and / or the higher initial pH. The removal level of run R2 is the lowest for the oil containing runs, likely due to the presence of the tannic and humic acids that are removed at lower levels than the oil – yet both contribute to measured turbidity.   A picture of the initial humic acid / tannic acid run that included oil-

water emulsion is shown in the picture below. The feed solution is shown on the left and the treated and filtered solution on the right.   The filtered solids can be seen on the filter paper held by the strainer.

4.1.1.4   Silt – Mock Solutions: The silt was obtained from a local creek bed. The mixture contained some visible solids that settled with time.   The solution was filtered (11 micron) to provide the feed solution for the test runs. These runs, R23 and R24, were conducted at different initial pH levels and slightly different solution makeup.   Both runs gave high removal levels (99.95 and 99.64%).

4.1.1.5   Hydrocarbon Condensate – Real Water: The last suspended solid study was conducted late in the project and consisted of real water obtained from a coal cleaning operation. The solution was of low conductivity as reflected in the low amperage level at 100 volts.   The feed was jet black and had a very odorous and visually obvious organic nature. The solution left a brownish film adhering to glass container walls. In the first few runs (R96 – R98) conducted at pH 6, there was little if any sign of coagulation and settling following treatment. Good removal levels (>99.5%) were obtained for higher amperage (run R99) and lower pH (runs R101 and R102).

4.1.2   Arsenic / Silica Removal

Initial studies began with a field sample (herein called the Oregon feed) from an industrial facility.

The Oregon feed had high arsenic levels (average of 210 mg/L) and relatively high silica levels (average of 35 mg/L). The Oregon feed pH was measured to be in the range of 3.03 to 3.33. As can be seen in the sequence of runs R26, R36, and R37, and as depicted below, arsenic and silica removal increased with increasing amperage although silica removals were substantially below arsenic removals.

Run #	amperage	Arsenic % removal	Silica % removal
R26	0.6	32.4	0
R36	10	59.9	2.9
R37	17.5	79.2	5.7

One and two-pass runs were made in R54 through R57. First pass removal levels for arsenic averaged 58% and increased to a total removal level of 86% after the second pass. First pass removals for silica averaged 1.5% and increased to an average of 17% after the second pass.

Mock solutions of arsenic and silica contained much lower amounts of both arsenic and silica (averages of 6.6 and 51 mg/L respectively). The mock solutions were of pH from 7.08 to 9.33 – much higher than the Oregon feed. The table below shows low removal levels at an amperage of 1 and dramatically higher removal levels of both arsenic and silica at amperage levels of 4 and 10.

Run #	amperage	Arsenic % removal	Silica % removal
R29	1	24.2	26
R30	4	97.9	97.8
R34	10	99.5	97.7
R35	10	99.3	97.5

4.1.3   Calcium Removal

More determinations of calcium removal were made than for any other species. This was because in-house titration analysis of calcium could be done simply and quickly. As opposed to most other contaminant studies that focused on and contained the contaminant against a base or background solution, most of the calcium determinations were of the background calcium level present in the various contaminant studies. In Table 4.3 it may be seen that removal levels varied dramatically from low values of zero (for both the iron and aluminum blades) and high values of 88 and 89% respectively for some iron and magnesium blade runs.

The many variables present and exercised in these runs complicated the correlation of calcium removals with system variables. In an early series of runs, that include R24 at a pH of 11, it was evident that at that high pH, calcium was precipitating from the feed solution even prior to the EC run. Thus the removal of run R24 could not be attributed to EC effects.

Three studies were undertaken to compare iron versus magnesium blades for both silica and calcium removal. The silica results will be discussed in a later section along with other silica studies. The first study involved a mock solution and runs R69 through R74. The feed calcium level was 28 mg/L. Higher amperage of 15 did not result in a significant increased removal than that at an amperage of 8 (79% as opposed to 76%). However, the magnesium blades averaged a removal of 87% versus 59% for the iron blades. The effect of pH over the range of 8.65 to 10.95 appeared to have little if any effect (runs R69 through R72).

The second study involved a cooling tower water with a calcium level of 189 mg/L. Again, the increase in removal due to amperage between 8 and 15 was minor (13 and 14%) however, the difference between magnesium and iron blades was significant (18 to 9%). As with several other runs, the comparison of removal levels between the two studies showed decreased removal levels with increasing concentration of the contaminant.

The third study used a mock solution with a calcium level of 38.8 mg/L. In addition to comparing blades and amperage levels as in the first two studies, this study (runs R84 through R89) looked at the increased removal of a second treatment pass over the first pass. Calcium removals increased significantly on the second pass. Total removals after the second pass for the iron blades were 35% (amperage 8) and 69% (amperage 15) versus first pass removals of 6% (amperage 8) and 28% (amperage 15). For the magnesium blade run, done only at amperage of 8, the total removal after the second pass was 63% compared to a first pass removal of 11%. An interesting sidelight of this set of runs was that the mock solutions included 5 ppm of an antiscalant for silica. The presence of the silica antiscalant had a negligible effect on silica removal (3rd study compared to the first study) but a dramatic effect on inhibiting calcium removal. In the first study the average calcium removal was 77%. In the third study, where antiscalant was present at 5 ppm, the average removal (first pass) was 15%.

4.1.4 Metals Removal

Several different studies addressed metal removal. The initial study looked at removal levels from a mix (soup) of 11 metals. The metals included Al, As, Ba, Cd, Cs, Cr, Cu, Fe, Si, Sr, and Zn. In making up the metal soup the target was to have individual metal levels close to 10 mg/L. This proved to be impossible due to solubility limits and there was a significant precipitate formed in the feed solution. The feed solution used in the runs was filtered (11 micron) to remove most of the precipitated material. The resulting feed concentrations of the metals ranged from 0.23 mg/L for barium to 11 mg/L for cesium. Variables in the studies included pH (values of 6, 7, and 8) and amperage (values of 1, 8, and 15). The results are displayed in the following series of box diagrams which show amperage in the horizontal direction and pH in the vertical. Runs were conducted corresponding to conditions at the corner points and the center point of the box. Values entered in the box are the removal levels.

In the boxes, the term 'neg' refers to cases where levels in the treated solution were higher than in the feed solution, an impossibility. In several cases the level in the treated solution was reported as below the detection limit. In these cases the removal is denoted as being greater than the number given which is based on the detection limit level. In all cases, removal levels at 15 amps are as high as or higher than removal levels at 1 amp. There are several instances where the removal level at the intermediate amperage of 8 is the highest of the 5 values. The effect of pH over this small range (6 to 8) does not yield a consistent trend.

The removal levels for some metals are consistently high (Cr, Cu), some have a mix of intermediate and high values (As, Cd, Si, Zn), one has a mix of very low values with very high values (Fe), one has a mix of low and intermediate values (Al) and some have consistently low values (Ba, Cs, Sr).

In most of the EC runs conducted after the metal soup study and involving metals, an attempt was made to make the runs at pH 7 and amperage of 8 that corresponds to the midpoint of the metal soup runs.   This allows comparison of the removal results from different studies to be made at similar run conditions.

Some of the metals were studied individually in runs R63-R68, R90, and R91.   The runs were conducted at pH 7 and an amperage of 8. The following table gives removal levels for these runs.

Run #	metal	% removal	comment
R63	Cr	>99.8	
R64	Cr	>99.8	conducted at salinity of 35,000 mg/L
R65	Ba	0.00	
R66	Cd	>93.7	
R67	Sr	9.41	
R68	Sr	24.7	conducted at salinity of 35,000 mg/L
R90	Cs	0.00	
R91	Ag	>89.8	

The removal levels for Cr, Ba, Cd, Sr, and Cs were in general agreement with the removal levels of these ions in the metal soup runs.

In run R90, some of the background ions were analyzed for removal levels. The results were:

Run #	metal	% removal
R90	Na	0.00
R90	Mg	17.5
R90	Mn	0.00

Silica removal was studied in the previously mentioned arsenic / silica runs.   In addition, several runs (R69-R78; R84-R89) were conducted focusing on silica removal. The variables included blade material (iron and magnesium), pH (7 to 11), amperage (8 and 15), and number of passes (1 and 2).   The calcium removal results from these same studies was reported in the earlier discussion of calcium.   In all of these runs, silica removal levels were high ranging from 85.2 to 99.9%. Consequently the effects of variables is difficult to discern. Removals increased somewhat with amperage and with the second pass. pH appeared to have little effect as did the blade material.   One of the studies conducted (runs R84 – R89) included a silica antiscalant. As previously mentioned, the antiscalant reduced the removal levels of calcium but had no obvious effect on silica removal.

A separate study was conducted looking at whether the relative removal levels of a 'high' and a 'low' removal metal would change between a single pass and a double pass.   The contaminants in these runs (R58, R59) included Cr, Sr, and Ba.   Removal levels increased only slightly with the second pass and removal levels were similar to those found in the metal soup study.

Aluminum	pH		amperage	
		1	8	15
	8	11.1		neg
	7		56.9	
	6	>28.6		>28.6

Arsenic	pH		amperage	
		1	8	15
	8	45.0		>90.0
	7		>97.6	
	6	>75.0		>75.0

Barium		
0.00		neg
	30.0	
neg		neg

Cadmium		
>99.0		>99.0
	>99.6	
31.6		99.1

Cesium		
0.00		9.1
	9.1	
0.00		0.00

Chromium		
95.5		>99.5
	>99.5	
88.0		>99.5

Copper		
>84.8		>84.8
	>92.1	
>96.7		>96.7

Iron		
>83.3		>83.3
	>92.5	
---		neg

Silicon		
32.8		84.7
	87.2	
13.3		84.3

Strontium		
12.9		28.6
	16.7	
1.4		1.4

Zinc		
>93.8		>93.8
	>97.7	
>54.5		>99.5

Run #	metal	# passes	% removal
R58	Cr	1	>99.8
R59	Cr	2	>99.8
R58	Sr	1	13.0
R59	Sr	2	15.9
R58	Ba	1	0.0
R59	Ba	2	3.5

Another study focused on the relative feed level of Sr and Cr.   The ratios of ions varied in the three runs (R60 – R62) from 10:1, to 5:5, to 1:10.   There was little effect on the consistently high level of Cr removal but a dramatic effect on Sr removal as seen in the following table.

Run #	metal	ratio Sr:Cr	% removal
R60	Cr	10:1	>99.8
R61	Cr	5:5	>99.97
R62	Cr	1:10	95.6
R60	Sr	10:1	2.5
R61	Sr	5:5	93.9
R62	Sr	1:10	85.3

Sr removal levels in runs R61 and R62 were much higher than in the metal soup runs.

A final metal study was conducted with Al as the contaminant in runs R78-R83. The variables were amperage and flow rate (residence time). Results are displayed in the following diagram.

	amperage		
8		19.5	61.0
6		>87.8	
4		77.3	76.6

Lo flow   high flow

The low removal level at low flow and higher amperage is the most outstanding feature of the data set and a surprising one in that one would expect the high amperage and low flow (longest residence time) to yield the highest removal levels.

4.1.5   Radionuclide Removal

Non-radioactive isotopes of radioactive species were run as surrogates for Cesium, iodine, and strontium. The following table shows removal levels for the four runs, R43-R46.

Contaminant	Run #	pH	amperage	removal %
Strontium	R43	6	1	98.7
Strontium	R44	6	15	73.5
Strontium	R45	8	1	99.1

Strontium	R46	8	15	91.5
Cesium	R43	6	1	13.3
Cesium	R44	6	15	13.3
Cesium	R45	8	1	13.3
Cesium	R46	8	15	13.3
Iodine	R43	6	1	----
Iodine	R44	6	15	8.3
Iodine	R45	8	1	8.3
Iodine	R46	8	15	>91.7

Strontium was removed at relatively high levels (>73%) in all runs. Cesium had a low (13.3%) removal in all runs and the removal of iodine was low except for the higher pH and higher amperage run where it rose significantly to >91.7.

Table 4.4 provides a summary table for the metals removals attained in different studies.

4.1.6   Perchlorate, Phosphate, and Nitrate Removal

All of these contaminants were put in one solution and runs were made at an amperage of 8 (R94) and an amperage of 15 (R95).   It is interesting to note that the higher amperage did not improve removal levels.   Only phosphate was removed at a high level (>96.16% in both runs). Perchlorate removal was 17.3% and 11.0% for the two runs. Nitrate removal was even less at 6.8% and 1.5% for the two runs.

4.1.7   Pesticide Removal

These runs (R103 to R105) were made by an affiliate of Power Water Systems. The four pesticides, DDT, Chlorpyrifos, Lindane, and Malathion were all present in DI water in the same feed sample.   Three different amperages were studied: 0.5, 1, and 2.5.   The feed levels of the contaminants ranged from 16 to 81 ppb.   The following table shows removal levels attained at the different amperages.

Pesticide	0.5 amps	1.0 amps	2.5 amps
DDT	83.8	86.9	98.1
Chlorpyrifos	30.0	32.5	90.5
Lindane	46.8	49.4	99.0
Malathion	95.9	37.0	>99.0

Either the 95.9% removal of Malathion at 0.5 amp or the 37% removal at 1.0 amp is likely incorrect.   Except for this one glitch, removals increase with increasing amperage.

4.1.8   Other Organics and Biologicals

Several challenges arose during considerations of conducting studies on various organic and biological contaminants.   First, the study of organics at low levels of concentration meant that, typically, GC-MS analysis was required. For an EC study with multiple runs, this becomes quite

Table 4.4. Metal Removals from Different Runs

STUDY:	metal soup avg of 5	metal soup mid point	individual metals	Sr, Cr, Ba 1 pass	Sr. Cr. Ba 2 passes	Sr:Cr 10:1	Sr:Cr 5:5	Sr:Cr 1:10	arsenic-silica studies	radionuclide study	silica study	aluminum time study	SS removal studies	anion study
RUN #'s	38-42	38-42	63-68 90-92	58	59	60	61	62	26-37 54-57	43-46	69-78 84-89	79-83	1-24 96-102	94-95
Metal	Removal levels (%)													
Cr	>96.4	>99.5	99.8	>99.75	>99.97	>99.78	>99.97	95.6	---	---	---	---	---	---
Cu	>91	>92.1	---	---	---	---	---	---	---	---	---	---	---	---
Zn	>87.9	>97.7	---	---	---	---	---	---	---	---	---	---	---	---
Cd	>85.7	>99.6	>93.7	---	---	---	---	---	---	---	---	---	---	---
As	>76.5	97.6	---	---	---	---	---	---	24.2 to 99.5	---	---	---	---	---
Fe	>64.8	>92.5	---	---	---	---	---	---	---	---	---	---	---	---
Ag	---	---	>89.8	---	---	---	---	---	---	---	---	---	---	---
I	---	---	---	---	---	---	---	---	---	8.3 to 91.7	---	---	---	---
Si	60.5	87.2	---	---	---	---	---	---	0.0 to 97.8	---	86.2 to 99.6	---	---	---
Al	>25	56.9	---	---	---	---	---	---	---	---	---	19.5 to >87.8	---	---
Ca	---	---	13.0 to 59.6	21.1	71.8	33	56.9	88.1	---	---	6.2 to 89.3	---	0 to 33.1	9.0 to 47.2
Mg	---	---	17.5	---	---	---	---	---	---	---	---	---	---	---
Sr	12.2	16.7	9.4	13	15.9	2.5	93.85	86.3	---	73.5 to 99.1	---	---	---	---
Ba	6	30	0	0	3.5	---	---	---	---	---	---	---	---	---
Cs	3.6	9.1	0	---	---	---	---	---	---	13.3	---	---	---	---
Na	---	---	0	---	---	---	---	---	---	---	---	---	---	---
Mn	---	---	0	---	---	---	---	---	---	---	---	---	---	---

costly.   Second, many organics readily adhere to polymer surfaces and the surfaces thus provide an uncontrolled sink for the organics that cannot easily be taken into account.   Third, the costs involved with procuring surrogates for various organic and biological contaminants was, in general, high.   Finally, charges quoted for conducting the EC studies at sites/labs that normally work with biologicals were very high.   Consequently, the decision was made to spend project funds on more cost-effective studies.

### 4.1.9   General Observations

4.1.9.1   Color:
- Treatment generally changed the color of solution depending on the contaminants and the blade material
- In a case (such as the hydrocarbon condensate runs) where the amperage was insufficient to cause coagulation and separation, the feed solution remained relatively unchanged in color upon treatment. With sufficient amperage, visible coagulation and separation took place, the solution color grew cloudier and darker. When the system was 'overpowered' such as in some early oil-water emulsion runs, the excessive amount of floc and the deeper color changes in the solution were obvious.
- Iron blades gave a green color that increased with amperage level and thus electrode dissolution level
- In nearly all cases filtering of the treated solution through an 11 micron paper filter removed all color from the solution.   In only a few cases was there a slight discoloration remaining in the treated and filtered solution.

4.1.9.2   ORP:
- ORP was positive in all feed solutions ranging from a low value of 23 (runs R69 and R70) to a high value of 548 (run R42).
- The feed ORP values were a function of pH as shown in the following box diagram.   The values entered in the box are the feed ORP values from the metal soup runs R38 – R42.

	8	169 169		
pH	6	258		Feed
	4	548 548		

<center>1   8   15
amperage</center>

- ORP of the treated solutions were measured typically within a few minutes of the treatment
- The ORP values decreased significantly with treatment as shown in the next box diagram corresponding to the same set of runs previously mentioned.

```
            ┌──────────────────────┐
         8  │   -271        -575   │          Treated feed
   pH    6  │          -587        │
         4  │   -221        -565   │
            └──────────────────────┘

              1     8    15
                 amperage
```
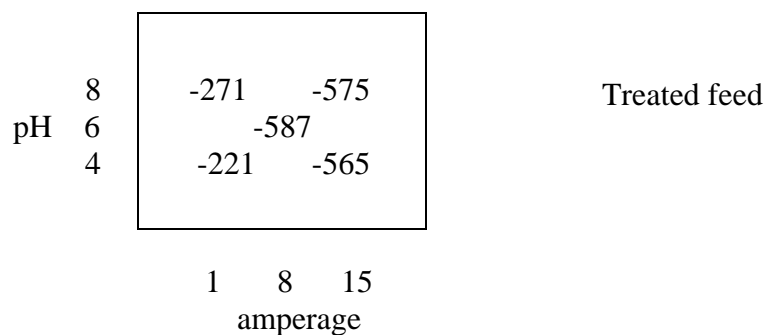
- The ORP values decreased with increasing amperage and possibly increasing pH
- The ORP values decreased with time and possibly due to the filtering as shown in the next box diagram corresponding to treated and filtered feed from the same set of runs. The filtering was done on the order of 5 to 15 minutes after treatment.

```
            ┌──────────────────────┐
         8  │   -162        -316   │
   pH    6  │          -238        │
         4  │    -82        -208   │
            └──────────────────────┘

              1     8    15
                 amperage
```
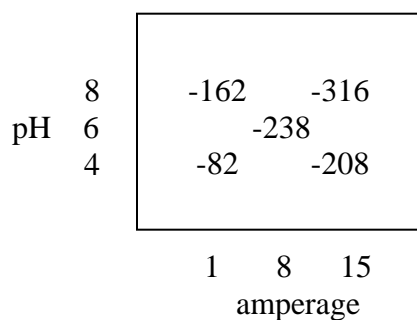
- The effects of amperage and pH are evident in the results: ORP decreasing with increased amperage and increased pH.
- In the early oil-water emulsion runs, the treated solution was captured in a series of 5 separate containers to determine any changes between the initially treated volume contained in the EC unit at power on and later treated volumes that flowed into the EC unit.
- The sequence of these 5 ORP and temperature values from Run R9 (a run with excessive overpowering) for non-filtered samples taken during a run over a period of minutes was:

Sample #	ORP	Temperature
1	-739	29C
2	-670	32
3	-606	35
4	-570	37
5	-560	38

At the high levels of overpowering, the ORP values tended to decrease with subsequent samples and the temperature of the samples increased.

- Initial ORP values of various early runs track with the amperage. The following values correspond to the initial samples from the designated runs.

Run #	amperage	Sample #1 ORP	Sample #5 Temperature
R9	15	-739	38C
R10	9	-715	31
R11	3	-----	28
R12	5	----	30
R13	4	-650	25
R14	0.9	-333	24.5
R15	0.75	-267	25
R16	0.7	-280	24
R17	0.75	-215	23.5

The run sequence begins with the high overpowering of the system and reflects changes as the powering decreases. The ORP values decrease as the amperage decreases and the temperature of the final sample tends to decrease.   As previously noted, removal levels of the turbidity did not decrease as amperage was decreased.   Subsequent EC runs avoided the high overpowering of the solution and consequently the initial ORP values and the final temperature values found in later runs were less than they might otherwise be.

4.1.9.3 Temperature:
- Temperature changes due to treatment were monitored in the early oil-water emulsion runs. As shown above in the discussion of ORP values, in the situation of overpowering the solution, temperature increased as treatment continued.
- As the power level decreased from run R9 to run R17 (as shown above) the temperature increase due to treatment decreased dramatically.
- The temperature of the feed solution was studied in runs R18 through R20. The feed temperature in these runs was 8C, 22.7C, and 50C respectively. No discernable effect in removal levels was found. However the lack of variability in the results with the consistently high removal values did not allow for simple assignment of effects.

4.1.9.4 TS:
- The total solids results of the oil-water emulsion runs were discussed with those runs.
- After the avoidance of overpowering the system and associated wasted electrode material and wasted energy, the material balances were more closely closed.
- Although total solids continued to be measured, its value as an indicator of treatment was minimal

4.1.9.5 pH:
- pH was measured for the feed and the treated solutions.
- pH increased due to treatment in all runs except those beginning at pH levels about about 11
- the pH increase with treatment lessened as the starting (feed) pH increased
- the data may support that pH change due to treatment was greater for the magnesium blades than for the iron blades than for the aluminum blades

4.1.9.6 Residence Time and Multi-pass Runs:

- Residence time was studied as part of the oil-water runs where the pump setting took on values of 4, 8, and double the flow at the 8 setting (with the aid of a separate pump). Due to the very high removal levels in all of these runs (R2, R4-R22) any effects of residence was could not be determined.
- Residence time was also studied in runs R79 through R83. The data were discussed in the metal removal section.   No clear influence of residence time was delineated.
- The effect of a second pass on the overall removal was looked at in several studies as discussed above as part of the individual studies.   This included the arsenic / silica runs R54 through R57, calcium and the Cr, Sr, Ba runs R58 and R59, and calcium and silica in runs R84 through R89. The second pass resulted in increased (additional) removal of contaminants in all cases.

4.1.9.7 Power:

- The nominal power ranged from a low of 2 watts (run R22) to a high of 1665 watts (run R8); both values occurring in the oil-water emulation runs.   The turbidity removal at 2 watts was equal to the removal at higher power levels.
- In other studies, not involving suspended solids or particulates, removal levels typically increased with increasing power.

4.2   AMICON MEMBRANE DATA SUMMARY

Table 4.5 lists the Amicon cell runs including the test solutions and normalized flow data obtained from the sequence of 8 flow determinations made in the fouling studies.   Most of the run data are plotted in Figure 1.   Figure 1a shows the sequence of 8 flow determinations for DI water, distilled water and the base solution used in the oil-water emulsion studies. Figure 1b shows that sequence of flow determinations for three oil-water emulsion runs.   Figure 1c shows a comparison of EC treated product water (run R9) with DI runs.   Patterns from running silt and tannic and humic acids are shown in Figures 1d and 1e.   Finally, Figure 1f shows the pattern resulting from distilled water where the membrane was not removed from the test cell between determinations.

4.2.1   Observations on the Data Patterns

Relative to the initial normalized flux level (by definition 1.00) the decrease in flux values due to dipping the membrane in the test solutions are estimated to be:

Test solution	Reduction from DI water flux
Oil-water emulsion	70%
Tannic acid	20
Humic acid	20
Silt	20
Treated oil-water emulsion	0
Distilled water	0
DI water	0

Table 4.5. Amicon Cell Membrane Test Data - sequence of 8 flow determinations

AM5	AM6	AM7	AM8	AM9	AM10	AM11	AM12	AM13
25% base o/w 100 mg/L	25% base o/w 100 mg/L	25% base o/w 100 mg/L	o/w R14 product	filtered silt	filtered silt	10 mg/L humic	10 mg/L humic	10 mg/L tannic
1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1.00	1.00	1.00	1.00	1.00	1.00	1.00	1	1
0.49	0.24	0.25	0.86	0.84	0.78	0.86	0.81	0.82
0.38	0.22	0.22	0.86	0.82	0.75	0.79	0.76	0.81
0.30	0.18	0.17	0.74	0.46	0.44	0.65	0.59	0.69
0.09	0.07	0.04	0.58	0.21	0.22	0.44	0.39	0.59
0.06	0.08	0.03	0.67	0.22	0.35	0.39	0.48	0.63
0.05	0.08	0.03	0.67	0.32	0.33	0.49	0.48	0.61

AM14	AM15	AM17	AM18	AM19	AM20	AM21	AM22	AM23
DI only	old base	distilled only	DI only	old base	DI	Distilled	PAC	10 mg/L tannic
1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
0.76	0.96	0.92	0.86	0.96	0.77	0.83	0.96	0.90
0.71	0.95	0.91	0.78	0.93	0.87	0.89	1.01	0.98
0.73	0.90	0.95	0.80	0.96	0.85	0.82	0.78	0.84
0.66	0.88	0.90	0.77	0.87	0.86	0.89	1.00	0.87
0.66	0.89	0.88	0.72	0.92	0.82	0.82	0.89	0.84
0.63	0.86	0.90	0.72	0.89	0.95	0.78	0.96	0.89

AM24	AM25	AM26	AM27	AM28	AM29	AM30	AM31	AM32
100% base	PAC	distilled	distilled	cont.* distilled	cont.* distilled	cont.* distilled	DI	100% base
1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
0.77	0.82	0.98	0.97				0.93	0.90
0.78	0.86	0.98	0.97	0.97	0.96	0.99	0.94	0.88
0.65	0.83		0.92				0.93	0.83
0.68	0.85		0.96	0.96	0.96	0.95	0.90	0.81
0.63	0.78		0.91				0.84	0.91
0.67	0.80		0.92		0.96	1.02	0.86	0.90

* cont. distilled refers to runs made without taking the cell apart between pressurizations
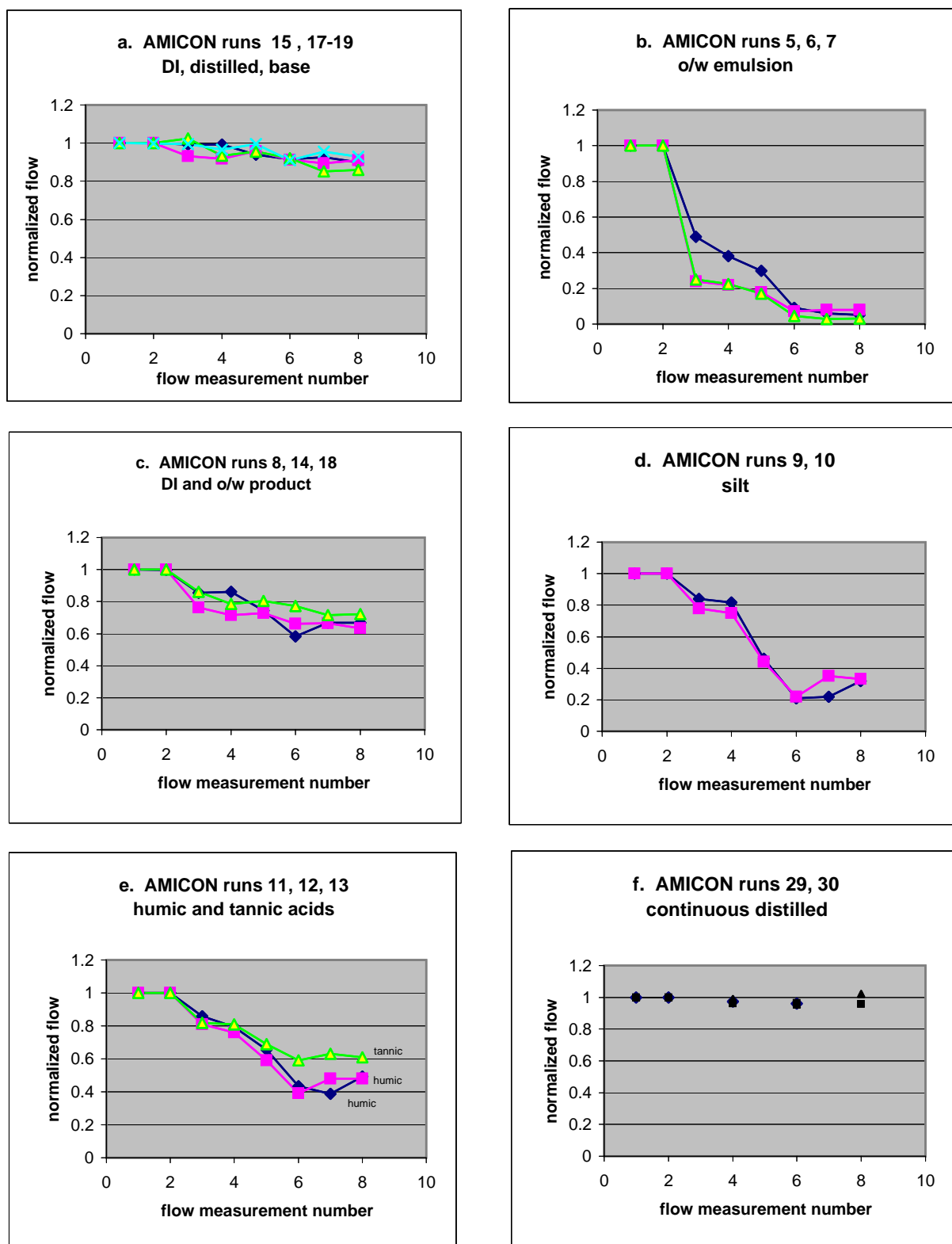
Figure 4.1.   Amicon Cell Membrane Data Patterns

Base solution   0

Relative to the flux determined after dipping the membrane into the test solutions, the flux decreases due to processing the test solution are estimated to be:

	Reduction from
Test solution	**dipping flux**
Silt	75%
Oil-water emulsion	70
Humic acid	50
Tannic acid	30
Treated oil-water emulsion	30
Distilled water	5
DI water	5
Base solution	5

Note the different hierarchy of the test solutions in this effect.

Relative to the flux level measured after processing the test solution, the flux increases from processing DI water after rinsing the membrane surface with DI water are estimated to be:

	Increase from
Test solution	**test solution flux**
Silt	60%
Humic acid	18
Treated oil-water emulsion	15
Tannic acid	4
Distilled water	0
DI water	0
Base solution	0
Oil-water emulsion	negative

4.3   ENERGY COST CALCULATIONS

Table 4.6 presents the energy cost projections by EC run evaluated at an electrical cost of $0.08/kWh. The next to last column gives the energy cost in units of $/kgal based on the run conditions (energy used to treat a given amount of solution).   The values range from a low of less than $0.01 to a high of $10.64/kgal.   The last column gives the costs in units of $/m3.   The high costs do not, in general, correspond to the best removal rates obtained.   Further, the research runs made no attempt to optimize removal results. Consequently, the costs should be viewed as conservative estimates.

It is important to note the energy cost in the Powell Water Systems' commercial EC units will be 1/4th that of the bench-scale test unit due to design differences.

Table 4.6. Energy Cost Projections by EC Run

LATEX PAINT

RUN #	Contaminate	Other Contaminants Special Conditions	Pump Setting	Nominal Voltage	Nominal Amperage	Nominal Power	% REMOVAL	Energy cost at $0.08/kWh ($/kgal)	Energy cost at $0.08/kWh ($/m3)
R1	latex paint		4	100	13	1300	99.92	8.30	2.19

OIL-WATER EMULSION

RUN #	Contaminate	Other Contaminants Special Conditions	Pump Setting	Nominal Voltage	Nominal Amperage	Nominal Power	% REMOVAL	Energy cost at $0.08/kWh ($/kgal)	Energy cost at $0.08/kWh ($/m3)
R2	100 ppm oil	+ 10ppm tannic & humic acid	4	100	13	1300	99.61	9.90	2.62
R4	100 ppm oil		4	100	15.5	1550	98.30	8.30	2.19
R5	100 ppm oil		4	100	15	1500	99.44	8.30	2.19
R6	100 ppm oil		4	100	13	1300	99.61	8.30	2.19
R7	200 ppm oil		4	100	13	1300	99.74	8.30	2.19
R8	100 ppm oil		4	90	18.5	1665	99.79	10.64	2.81
R9	100 ppm oil		8	100	15	1500	99.45	4.55	1.20
R10	100 ppm oil	higher salinity	8	50	9	450	99.72	1.36	0.36
R11	100 ppm oil	lower salinity	8	50	3	150	99.77	0.45	0.12
R12	100 ppm oil	medium salinity	8	50	5	250	99.83	0.76	0.20
R13	100 ppm oil	lower power	8	25	4	100	99.78	0.3	0.08
R14	100 ppm oil	lower power	8	5	0.9	4.5	99.74	0.01	0.0026
R15	100 ppm oil	higher oil content	8	5	0.75	3.75	99.93	0.01	0.0026
R16	100 ppm oil	+0.3g/L NaHCO3	8	5	0.7	3.5	99.67	0.01	0.0026
R17	100 ppm oil	+0.3g/L NaHCO3; low temperature	8	5	0.75	3.75	99.74	0.01	0.0026
R18	100 ppm oil	+0.3g/L NaHCO3	8	5	0.6	3	99.54	0.01	0.0026
R19	100 ppm oil		8	100	0.4	40	99.85	0.12	0.03
R20	100 ppm oil	high temperature	8	100	0.4	40	99.91	0.12	0.03
R21	100 ppm oil	high flow	2x '8'	5	0.6	3	99.71	0.0045	0.0012
R22	100 ppm oil	high flow	2x '8'	5	0.4	2	99.55	0.003	0.0008

TANNIC / HUMIC ACID

RUN #	Contaminate	Other Contaminants Special Conditions	Pump Setting	Nominal Voltage	Nominal Amperage	Nominal Power	% REMOVAL	Energy cost at $0.08/kWh ($/kgal)	Energy cost at $0.08/kWh ($/m3)
R2	10 ppm tannic & humic acid	100 ppm oil	4	100	15.5	1550	98.2997118	9.90	2.62
R3	same		4	100	15	1500	87.9341865	8.30	2.19
R25	same		4	90	14	1260	93.2938856	8.05	2.13

SILT

RUN #	Contaminate	Other Contaminants Special Conditions	Pump Setting	Nominal Voltage	Nominal Amperage	Nominal Power	% REMOVAL	Energy cost at $0.08/kWh ($/kgal)	Energy cost at $0.08/kWh ($/m3)
R23			8	5	1	5	99.9509804	0.02	0.0053
R24		+0.3g/L NaHCO3; pH 11.11	8	5	1	5	99.6410256	0.02	0.0053

ARSENIC / SILICA

RUN #	Contaminate	Other Contaminants Special Conditions	Pump Setting	Nominal Voltage	Nominal Amperage	Nominal Power	% REMOVAL	Energy cost at $0.08/kWh ($/kgal)	Energy cost at $0.08/kWh ($/m3)
R26	As	Oregon sample	8	100	0.6	60	32.42	0.18	0.05
R26	Si	Oregon sample	8	100	0.6	60	0.00	0.18	0.05
R27	As	Oregon sample; high amp	8	25	7	175	---	0.53	0.14
R27	Si	Oregon sample; high amp	8	25	7	175	---	0.53	0.14
R28	As	Oregon sample; low amp	8	5	1	5	---	0.02	0.0053
R28	Si	Oregon sample; low amp	8	5	1	5	---	0.02	0.0053
R29	As	low amp; mock solution	8	27	1	27	24.24	0.08	0.02
R29	Si	low amp; mock solution	8	27	1	27	26.00	0.08	0.02
R30	As	high amp; mock solution	8	98	4	392	97.88	1.19	0.3144
R30	Si	high amp; mock solution	8	98	4	392	97.80	1.19	0.3144
R34	As	mock solution	8	42	10	420	99.54	1.27	0.34
R34	Si	mock solution	8	42	10	420	97.74	1.27	0.34
R35	As	+NaCl; mock solution	8	24	10	240	99.30	0.73	0.19
R35	Si	+NaCl; mock solution	8	24	10	240	97.45	0.73	0.19
R36	As	Oregon sample; med. power.	8	12	10	120	59.91	0.36	0.10
R36	Si	Oregon sample; med. power.	8	12	10	120	2.86	0.36	0.10
R37	As	Oregon sample; high power	8	24	17.5	420	79.25	1.27	0.34
R37	Si	Oregon sample; high power	8	24	17.5	420	5.71	1.27	0.34
R54	As	Oregon sample; 1 pass	8	98	3.5	343	65.05	1.04	0.27
R54	Si	Oregon sample; 1 pass	8	98	3.5	343	3.13	1.04	0.27
R55	As	Oregon sample; 2nd pass	8	98	2	196	85.51	0.59	0.16
R55	Si	Oregon sample; 2nd pass	8	98	2	196	25.00	0.59	0.16
R56	As	Oregon sample; 1 pass	8	12	10	120	50.51	0.36	0.10
R56	Si	Oregon sample; 1 pass	8	12	10	120	0.00	0.36	0.10
R57	As	Oregon sample; 2nd pass	8	16	10	160	86.06	0.48	0.13
R57	Si	Oregon sample; 2nd pass	8	16	10	160	9.38	0.48	0.13

CALCIUM

								Energy cost	Energy cost

RUN #	Contaminate	Other Contaminants / Special Conditions	Pump Setting	Nominal Voltage	Nominal Amperage	Nominal Power	% REMOVAL	at $0.08/kWh ($/kgal)	at $0.08/kWh ($/m3)
R5	Ca	100 ppm oil	4	100	13	1300	29.16	8.30	2.19
R7	Ca	100 ppm oil	4	100	13	1300	33.05	8.30	2.19
R8	Ca	100 ppm oil	4	90	18.5	1665	2.59	10.64	2.81
R10	Ca	100 ppm oil; higher salinity	8	50	9	450	0.00	1.36	0.36
R11	Ca	100 ppm oil; low salinity	8	50	3	150	0.00	0.45	0.12
R12	Ca	100 ppm oil; medium salinity	8	50	5	250	0.00	0.76	0.20
R13	Ca	100 ppm oil; low power	8	25	4	100	0.00	0.3	0.08
R14	Ca	100 ppm oil; very low power	8	5	0.9	4.5	0.00	0.01	0.0026
R15	Ca	200 ppm oil	8	5	0.75	3.75	0.00	0.01	0.0026
R16	Ca	100 ppm oil; +0.3g/L NaHCO3	8	5	0.7	3.5	0.00	0.01	0.0026
R17	Ca	100 ppm oil; +0.3g/L NaHCO3, low temp.	8	5	0.75	3.75	6.05	0.01	0.0026
R21	Ca	100 ppm oil; high flow	2x 8	5	0.6	3	0.00	0.0045	0.0012
R22	Ca	100 ppm oil; low flow	2x 8	5	0.4	2	0.00	0.003	0.0008
R23	Ca	silt mixture	8	5	1	5	0.00	0.02	0.0053
R24	Ca	silt mixture; + 0.3g/L NaHCO3; high pH	8	5	1	5	19.44	0.02	0.0053
R58	Ca	metal soup; 1 pass	8	56	8	448	21.13	1.41	0.37
R59	Ca	metal soup; 2nd pass	8	58	8	464	71.82	1.26	0.33
R60	Ca	Sr, Cr	8	52	8	416	33.02	1.26	0.33
R61	Ca	Sr, Cr	8	52	8	416	56.94	1.26	0.33
R62	Ca	Sr, Cr	8	52	8	416	88.08	1.26	0.33
R63	Ca	Cr	8	52	8	416	---	1.26	0.33
R64	Ca	Cr, high salinity	8	<1	8	< 8	---	0.02	0.0053
R65	Ca	Ba	8	45	8	360	31.67	1.09	0.29
R66	Ca	Cd	8	50	8	400	22.47	1.21	0.32
R67	Ca	Sr, Cr	8	46	8	368	13.01	1.16	0.31
R68	Ca	Sr, high salinity	8	<1	8	<8	59.61	0.02	0.0053
R69	Ca	Si; Mg blade; 8 amp; high pH	8	40	8	320	89.25	0.97	0.26
R70	Ca	Si; Mg blade; 15 amp; high pH	8	71	15	1065	87.95	3.23	0.85
R71	Ca	Si; Mg blade; 8 amp; neutral pH	8	39	8	312	84.93	0.95	0.25
R72	Ca	Si; Mg blade; 15 amp; neutral pH	8	70	15	1050	84.93	3.18	0.84
R73	Ca	Si; 8 amp; neutral pH	8	43	8	344	53.31	1.04	0.27
R74	Ca	Si; 15 amp neutral pH	8	76	15	1140	65.44	3.46	0.91
R75	Ca	Si; Mg blade; 8 amp	8	40	8	320	17.39	0.97	0.26
R76	Ca	Si; Mg blade; 15 amp	8	76	15	1140	18.50	3.46	0.91
R77	Ca	Si; 8 amp	8	45	8	360	7.64	1.09	0.29
R78	Ca	Si; 15 amp	8	80	15	1200	10.34	3.64	0.96
R79	Ca	Al; low amp; low flow	4	20	4	80	13.27	0.51	0.13
R80	Ca	Al; medium amp; medium flow	6	32	6	192	16.99	0.81	0.21
R81	Ca	Al; high amp; low flow	4	40	8	320	49.27	2.04	0.54
R82	Ca	Al; high amp; high flow	8	45	8	360	14.74	1.09	0.29
R83	Ca	Al; low amp; high flow	8	23	4	92	7.76	0.28	0.07
R84	Ca	Si; 1 pass	8	40	8	320	6.17	0.97	0.26
R85	Ca	Si; 2nd pass	8	34	8	272	34.70	0.82	0.22
R86	Ca	Si; higher amp; 1 pass	8	73	15	1095	28.28	3.41	0.90
R87	Ca	Si; higher amp; 2nd pass	8	53	15	795	69.41	2.41	0.64
R88	Ca	Si; Mg blade; 1 pass	8	36	8	288	10.54	0.87	0.23
R89	Ca	Si; Mg blade; 2nd pass	8	30	8	240	63.24	0.73	0.19
R90	Ca	Fe	8	48	8	384	23.81	1.16	0.31
R94	Ca	ClO4, PO4, NO3	8	50	8	400	9.02	1.21	0.32
R95	Ca	ClO4, PO4, NO3; higher amp	8	89	15	1335	47.16	4.05	1.07

METAL SOUP

RUN #	Contaminate	Other Contaminants / Special Conditions	Pump Setting	Nominal Voltage	Nominal Amperage	Nominal Power	% REMOVAL	Energy cost at $0.08/kWh ($/kgal)	Energy cost at $0.08/kWh ($/m3)
R38	Al	pH 7; medium power; metal soup	8	52	8	416	56.92	1.26	0.33
R38	As	pH 7; medium power; metal soup	8	52	8	416	>99.05	1.26	0.33
R38	Ba	pH 7; medium power; metal soup	8	52	8	416	30.00	1.26	0.33
R38	Cd	pH 7; medium power; metal soup	8	52	8	416	>99.57	1.26	0.33
R38	Cs	pH 7; medium power; metal soup	8	52	8	416	9.09	1.26	0.33
R38	Cr	pH 7; medium power; metal soup	8	52	8	416	>99.50	1.26	0.33
R38	Cu	pH 7; medium power; metal soup	8	52	8	416	>92.06	1.26	0.33
R38	Fe	pH 7; medium power; metal soup	8	52	8	416	>92.54	1.26	0.33
R38	Si	pH 7; medium power; metal soup	8	52	8	416	87.18	1.26	0.33
R38	Sr	pH 7; medium power; metal soup	8	52	8	416	16.67	1.26	0.33
R38	Zn	pH 7; medium power; metal soup	8	52	8	416	>97.73	1.26	0.33
R39	Al	pH 8, low power; metal soup	8	4	1	4	11.11	0.01	0.0026
R39	As	pH 8, low power; metal soup	8	4	1	4	45.00	0.01	0.0026
R39	Ba	pH 8, low power; metal soup	8	4	1	4	0.00	0.01	0.0026
R39	Cd	pH 8, low power; metal soup	8	4	1	4	>99.00	0.01	0.0026
R39	Cs	pH 8, low power; metal soup	8	4	1	4	0.00	0.01	0.0026
R39	Cr	pH 8, low power; metal soup	8	4	1	4	95.50	0.01	0.0026
R39	Cu	pH 8, low power; metal soup	8	4	1	4	>84.85	0.01	0.0026
R39	Fe	pH 8, low power; metal soup	8	4	1	4	>83.33	0.01	0.0026
R39	Si	pH 8, low power; metal soup	8	4	1	4	32.81	0.01	0.0026
R39	Sr	pH 8, low power; metal soup	8	4	1	4	12.86	0.01	0.0026

RUN #	Contaminate	Special Conditions	Pump Setting	Nominal Voltage	Nominal Amperage	Nominal Power	% REMOVAL	Energy cost at $0.08/kWh ($/kgal)	Energy cost at $0.08/kWh ($/m3)
R39	Zn	pH 8, low power; metal soup	8	4	1	4	>93.75	0.01	0.0026
R40	Al	pH 8; high power; metal soup	8	90	15	1350	-22.22	4.09	1.08
R40	As	pH 8; high power; metal soup	8	90	15	1350	>90.00	4.09	1.08
R40	Ba	pH 8; high power; metal soup	8	90	15	1350	-4.35	4.09	1.08
R40	Cd	pH 8; high power; metal soup	8	90	15	1350	>99.00	4.09	1.08
R40	Cs	pH 8; high power; metal soup	8	90	15	1350	9.09	4.09	1.08
R40	Cr	pH 8; high power; metal soup	8	90	15	1350	>99.50	4.09	1.08
R40	Cu	pH 8; high power; metal soup	8	90	15	1350	>84.85	4.09	1.08
R40	Fe	pH 8; high power; metal soup	8	90	15	1350	>83.33	4.09	1.08
R40	Si	pH 8; high power; metal soup	8	90	15	1350	84.69	4.09	1.08
R40	Sr	pH 8; high power; metal soup	8	90	15	1350	28.57	4.09	1.08
R40	Zn	pH 8; high power; metal soup	8	90	15	1350	>93.75	4.09	1.08
R41	Al	pH 6; low power; metal soup	8	5	1	5	>28.57	0.02	0.0053
R41	As	pH 6; low power; metal soup	8	5	1	5	>75.00	0.02	0.0053
R41	Ba	pH 6; low power; metal soup	8	5	1	5	-84.62	0.02	0.0053
R41	Cd	pH 6; low power; metal soup	8	5	1	5	31.58	0.02	0.0053
R41	Cs	pH 6; low power; metal soup	8	5	1	5	0.00	0.02	0.0053
R41	Cr	pH 6; low power; metal soup	8	5	1	5	88.00	0.02	0.0053
R41	Cu	pH 6; low power; metal soup	8	5	1	5	>96.67	0.02	0.0053
R41	Fe	pH 6; low power; metal soup	8	5	1	5	---	0.02	0.0053
R41	Si	pH 6; low power; metal soup	8	5	1	5	13.25	0.02	0.0053
R41	Sr	pH 6; low power; metal soup	8	5	1	5	1.39	0.02	0.0053
R41	Zn	pH 6; low power; metal soup	8	5	1	5	54.55	0.02	0.0053
R42	Al	pH 6; high power; metal soup	8	90	15	1350	>28.57	4.09	1.08
R42	As	pH 6; high power; metal soup	8	90	15	1350	>75.00	4.09	1.08
R42	Ba	pH 6; high power; metal soup	8	90	15	1350	-153.85	4.09	1.08
R42	Cd	pH 6; high power; metal soup	8	90	15	1350	99.12	4.09	1.08
R42	Cs	pH 6; high power; metal soup	8	90	15	1350	0.00	4.09	1.08
R42	Cr	pH 6; high power; metal soup	8	90	15	1350	>99.50	4.09	1.08
R42	Cu	pH 6; high power; metal soup	8	90	15	1350	>96.67	4.09	1.08
R42	Fe	pH 6; high power; metal soup	8	90	15	1350	---	4.09	1.08
R42	Si	pH 6; high power; metal soup	8	90	15	1350	84.34	4.09	1.08
R42	Sr	pH 6; high power; metal soup	8	90	15	1350	1.39	4.09	1.08
R42	Zn	pH 6; high power; metal soup	8	90	15	1350	>99.55	4.09	1.08

RADIONUCLIDES

RUN #	Contaminate	Other Contaminants Special Conditions	Pump Setting	Nominal Voltage	Nominal Amperage	Nominal Power	% REMOVAL	Energy cost at $0.08/kWh ($/kgal)	Energy cost at $0.08/kWh ($/m3)
R43	Sr	pH 6; low power; Cs, I	8	2	1	2	98.65	0.01	0.0026
R43	Cs	pH 6; low power; I, Sr	8	2	1	2	13.33	0.01	0.0026
R43	I	pH 6; low power; Sr, Cs	8	2	1	2	---	0.01	0.0026
R44	Sr	pH 6; high power; Cs, I	8	50	15	750	73.54	2.27	0.60
R44	Cs	pH 6; high power; I, Sr	8	50	15	750	13.33	2.27	0.60
R44	I	pH 6; high power; Sr, Cs	8	50	15	750	8.33	2.27	0.60
R45	Sr	pH 8; low power; Cs, I	8	2	1	2	99.10	0.01	0.0026
R45	Cs	pH 8; low power; I, Sr	8	2	1	2	13.33	0.01	0.0026
R45	I	pH 8; low power; Sr, Cs	8	2	1	2	8.33	0.01	0.0026
R46	Sr	pH 8; high power; Cs, I	8	50	15	750	91.48	2.27	0.60
R46	Cs	pH 8; high power; I, Sr	8	50	15	750	13.33	2.27	0.60
R46	I	pH 8; high power; Sr, Cs	8	50	15	750	>91.67	2.27	0.60

Sr, Cr, Ba SINGLE AND DOUBLE PASS

RUN #	Contaminate	Other Contaminants Special Conditions	Pump Setting	Nominal Voltage	Nominal Amperage	Nominal Power	% REMOVAL	Energy cost at $0.08/kWh ($/kgal)	Energy cost at $0.08/kWh ($/m3)
R58	Sr	1 pass	8	56	8	448	13.04	1.41	0.37
R58	Cr	1 pass	8	56	8	448	>99.75	1.41	0.37
R58	Ba	1 pass	8	56	8	448	0.00	1.41	0.37
R59	Sr	2nd pass	8	52	8	416	15.94	1.26	0.33
R59	Cr	2nd pass	8	52	8	416	>99.75	1.26	0.33
R59	Ba	2nd pass	8	52	8	416	3.45	1.26	0.33

Sr:Cr RATIO

RUN #	Contaminate	Other Contaminants Special Conditions	Pump Setting	Nominal Voltage	Nominal Amperage	Nominal Power	% REMOVAL	Energy cost at $0.08/kWh ($/kgal)	Energy cost at $0.08/kWh ($/m3)
R60	Sr	10:1 ratio	8	52	8	416	2.53	1.26	0.33
R60	Cr	10:1 ratio	8	52	8	416	>99.78	1.26	0.33
R61	Sr	5:5 ratio	8	52	8	416	93.85	1.26	0.33
R61	Cr	5:5 ratio	8	52	8	416	>99.97	1.26	0.33
R62	Sr	1:10 ratio	8	52	8	416	86.25	1.26	0.33
R62	Cr	1:10 ratio	8	52	8	416	95.64	1.26	0.33

INDIVIDUAL METALS

RUN #	Contaminate	Other Contaminants Special Conditions	Pump Setting	Nominal Voltage	Nominal Amperage	Nominal Power	% REMOVAL	Energy cost at $0.08/kWh ($/kgal)	Energy cost at $0.08/kWh ($/m3)
R63	Cr		8	52	8	416	>99.78	1.26	0.32
R64	Cr	high salinity	8	<1	8	<8	>99.78	0.02	0.0053
R65	Ba		8	45	8	360	0.00	1.09	0.29

RUN #	Contaminate		Pump Setting	Nominal Voltage	Nominal Amperage	Nominal Power	% REMOVAL	Energy cost at $0.08/kWh ($/kgal)	Energy cost at $0.08/kWh ($/m3)
R66	Cd		8	50	8	400	>93.68	**1.21**	**0.32**
R67	Sr		8	48	8	384	9.41	**1.16**	**0.31**
R68	Sr	high salinity	8	<1	8	<8	24.71	**0.02**	**0.0053**
R90	Fe		8	48	8	384	---	**1.16**	**0.31**
R90	Na		8	48	8	384	0.00	**1.16**	**0.31**
R90	Mg		8	48	8	384	17.50	**1.16**	**0.31**
R90	Mn		8	48	8	384	0.00	**1.16**	**0.31**
R91	Cs		8	44	8	352	0.00	**1.07**	**0.28**
R92	Ag		8	44	8	352	>89.80	**---**	**---**

SILICA

RUN #	Contaminate	Other Contaminants Special Conditions	Pump Setting	Nominal Voltage	Nominal Amperage	Nominal Power	% REMOVAL	Energy cost at $0.08/kWh ($/kgal)	Energy cost at $0.08/kWh ($/m3)
R69	Si	8 amp; high pH	8	40	8	320	86.17	**0.97**	**0.26**
R70	Si	15 amp; high pH	8	71	15	1065	---	**3.23**	**0.85**
R71	Si	8 amp; neutral pH	8	39	8	312	89.25	**0.95**	**0.25**
R72	Si	15 amp; neutral pH	8	70	15	1050	97.85	**3.18**	**0.84**
R73	Si	8 amp; neutral pH	8	43	8	344	96.02	**1.04**	**0.27**
R74	Si	15 amp; neutral pH	8	76	15	1140	99.48	**3.46**	**0.91**
R75	Si	8 amp	8	40	8	320	94.09	**0.97**	**0.26**
R76	Si	15 amp	8	76	15	1140	95.61	**3.46**	**0.91**
R77	Si	8 amp	8	45	8	360	85.15	**1.09**	**0.29**
R78	Si	15 amp	8	80	15	1200	99.33	**3.64**	**0.96**
R84	Si	8 amp; 1 pass	8	40	8	320	88.10	**0.97**	**0.26**
R85	Si	8 amp; 2nd pass	8	34	8	272	99.39	**0.82**	**0.22**
R86	Si	15 amp; 1 pass	8	73	15	1095	99.55	**3.41**	**0.90**
R87	Si	15 amp; 2nd pass	8	53	15	795	99.85	**2.41**	**0.64**
R88	Si	8 amp; 1 pass	8	36	8	288	88.93	**0.87**	**0.23**
R89	Si	8 amp; 2nd pass	8	30	8	240	97.98	**0.73**	**0.19**

ALUMINUM & RESIDENCE TIME

RUN #	Contaminate	Other Contaminants Special Conditions	Pump Setting	Nominal Voltage	Nominal Amperage	Nominal Power	% REMOVAL	Energy cost at $0.08/kWh ($/kgal)	Energy cost at $0.08/kWh ($/m3)
R79	Al	4 amp; low flow	4	20	4	80	77.32	**0.51**	**0.13**
R80	Al	6 amp; medium flow	6	32	6	192	>87.80	**0.81**	**0.21**
R81	Al	8 amp; low flow	4	40	8	320	19.51	**2.04**	**0.54**
R82	Al	8 amp; high flow	8	45	8	360	60.98	**1.09**	**0.29**
R83	Al	4 amp; high flow	4	23	4	92	76.59	**0.28**	**0.07**

PERCHLORATE, PHOSPHATE, & NITRATE

RUN #	Contaminate	Other Contaminants Special Conditions	Pump Setting	Nominal Voltage	Nominal Amperage	Nominal Power	% REMOVAL	Energy cost at $0.08/kWh ($/kgal)	Energy cost at $0.08/kWh ($/m3)
R94	ClO4	8 amp	8	50	8	400	17.30	**1.21**	**0.32**
R94	PO4	8 amp	8	50	8	400	>96.16	**1.21**	**0.32**
R94	NO3	8 amp	8	50	8	400	6.75	**1.21**	**0.32**
R95	ClO4	15 amp	8	89	15	1335	10.97	**4.05**	**1.07**
R95	PO4	15 amp	8	89	15	1335	>96.16	**4.05**	**1.07**
R95	NO3	15 amp	8	89	15	1335	1.48	**4.05**	**1.07**

HYDROCARBON CONDENSATE

RUN #	Contaminate	Other Contaminants Special Conditions	Pump Setting	Nominal Voltage	Nominal Amperage	Nominal Power	% REMOVAL	Energy cost at $0.08/kWh ($/kgal)	Energy cost at $0.08/kWh ($/m3)
R96	carbon particulates	nonvisible sign of coagulation	4	100	0.5	50	---	**0.32**	**0.08**
R97	carbon particulates	minor coagulation	4	100	3.5	350	---	**2.24**	**0.59**
R98	carbon particulates	visible settling after treatment	4	95	8.5	807.5	---	**5.16**	**1.36**
R99	carbon particulates	good settling / separation	4	92	12.5	1150	99.94	**7.35**	**1.94**
R100	carbon particulates	good settling / separation	4	92	17.5	1610	---	**10.28**	**2.72**
R101	carbon particulates	good settling / separation	4	98	7	686	99.95	**4.38**	**1.16**
R102	carbon particulates	good settling / separation	4	100	2	200	99.70	**1.28**	**0.34**

PESTICIDES*

RUN #	Contaminate	Other Contaminants Special Conditions	Pump Setting	Nominal Voltage	Nominal Amperage	Nominal Power	% REMOVAL	Energy cost at $0.08/kWh ($/kgal)	Energy cost at $0.08/kWh ($/m3)
R103	DDT	0.5 amp	5	---	0.5	---	83.75	**---**	**---**
R103	Chlorpyrifos	0.5 amp	5	---	0.5	---	30.00	**---**	**---**
R103	Lindane	0.5 amp	5	---	0.5	---	46.84	**---**	**---**
R103	Malathion	0.5 amp	5	---	0.5	---	95.93	**---**	**---**
R104	DDT	1.0 amp	5	---	1	---	86.88	**---**	**---**
R104	Chlorpyrifos	1.0 amp	5	---	1	---	32.50	**---**	**---**
R104	Lindane	1.0 amp	5	---	1	---	49.37	**---**	**---**
R104	Malathion	1.0 amp	5	---	1	---	37.04	**---**	**---**
R105	DDT	2.5 amp	5	---	2.5	---	98.13	**---**	**---**
R105	Chlorpyrifos	2.5 amp	5	---	2.5	---	90.50	**---**	**---**
R105	Lindane	2.5 amp	5	---	2.5	---	99.04	**---**	**---**
R105	Malathion	2.5 amp	5	---	2.5	---	>99.00	**---**	**---**

* = runs conducted by an affiliate of Powell Water Systems

CHAPTER 5.

DISCUSSION OF RESULTS, CONCLUSIONS, RECOMENDATIONS

5.1   DISCUSSION OF EC RESULTS

The intent of the EC runs was not to optimize removal levels but to investigate removal of various contaminants over a range of operating and solution variables.   Consequently, the removal results should be considered as representing optimal EC processing.

5.1.1   Removal of Suspended Solids

The consistently highest removal levels at the low power occurred with suspended solids.   The removals of oil-water emulsions, silt, latex paint, and hydrocarbon condensate were all > 99% at relatively low power levels.   Very high removal levels were obtained at amperages as low as could be measured on the power supply.   Thus a minimum power threshold could not be detected.

The removal of humic and tannic acid which presented more of a mixture of dissolved and suspended solids gave somewhat lower removal levels – removals of 88, 93, and 98% in the three runs conducted.

In all cases final turbidity levels were quite low. The levels of the treated and filtered solutions (highest value was 0.66 NTU) were comparable or better than the turbidity of the laboratory tap water.

The high removal levels in the oil-emulsion runs did not allow interpretation of the effect of several operating variables, i.e., over the range of conditions studied there were no obvious effect on removal rate of pH, temperature, amperage, blade material residence time, and solution matrix.

The oil-water emulsion runs did provide an example of what happens when more than enough power is used to bring about removal of the suspended solids.   The excess energy did not increase removal levels and resulted in greater blade material loss, increased amount of floc, and higher treated solution temperature – all non-beneficial effects.

The hydrocarbon condensate runs provided an example of the effect of pH on removal levels. The feed pH was 6 and reduction of pH to levels of 5 and 4 dramatically increased the removal of the carbon particulates.

Relative to other removal studies, the removal of suspended solids appears to require less energy for good removal levels and allows very high removal levels.

5.1.2   Removal of Arsenic and Silica

These removal studies gave the first demonstration of a power threshold and thus an effect of amperage on removal levels.   Removal level increased with amperage over the range studied. The effect of solution makeup (matrix effect) was apparent when comparing the field sample removal levels (As and Si at levels of 210 and 35 mg/L respectively) with mock solution removal levels (As and Si at levels of 6.6 and 51/mg/L respectively).   In the field sample As removal levels were much higher than Si removal levels while in the mock example the removal levels were similar. Removal levels were higher in the mock solution which may reflect a pH effect (field sample pH of 3.0 and mock solution pH of 7 to 9). As removal levels ranged from 24 to 99.5%.   Silica removal levels ranged from 0.0 to 99.6%.

5.1.3   Removal of Calcium

The range of calcium removals (from 0.0 to 89%) was considerable. The effects of amperage and blade material were demonstrated and it is likely that over the many solutions studied the chemical matrix had an effect on removal level.

5.1.4   Removal of Metals

It appears that some metals are consistently removed at higher levels than others.   Cr, Cu, Zn, and Cd were removed at high levels whether in a metal soup containing several metal or in a solution containing only the metal in question (in both cases the metals were present in a base or background solution).   Other metals displayed a wider range of removal levels such as Si ranging from 0.0 to 99.6%. The 0.0 value occurred at low amperage and low pH and the highest value at high amperage and neutral pH.   Aluminum removals ranged from 20 to 88% although the low value may be questionable in view of all other Al removal levels. Other metals showing a range of removal levels include Fe (>65% to >93%), I (8 to 92%), and Sr (3 to 99.1%). In the case of Sr, the high removal level occurred at low feed level of 0.223 mg/L, pH 8, and low power.   Some metals were consistently removed at low levels. These included Cs and Ba.

Little if any effect of salinity was noted on removal levels.   However, the higher conductivity of the higher salinity solutions resulted in less power needed to provide a given amperage. Thus processing of higher salinity solutions is more energy cost-effective than processing lower salinity solutions.

In all cases where the treated solution was treated in a second pass through the EC unit, the contaminant removal levels increased.

5.1.5   Removal of Radionuclides

Sr removals were between 74 and 99%, Cs removal was at 13%, and I removal was low at 8% except for the high amperage run where it was >92%.   In other studies, Sr removal ranged from 3 to 94%. Cs, however, was removed at low levels (13%) in other studies.

The removal results for these three contaminants reflect the difficulty of developing a simple explanation of either cause and effect or removal mechanism. For Sr the results of the various runs indicate the effect of operating and solution variables on removal; however, correlation of effect with individual variables is difficult.   For Cs, removal levels in all studies were consistently low.   For I, the effect of increased amperage at pH 8 (as opposed to pH 6) apparently caused the dramatic increase in removal level.

5.1.6   Removal of Perchlorate, Phosphate, and Nitrate

In this limited study, phosphate removal was high, and removal of perchlorate and nitrate was low. When compared with high removal levels in some literature cases, these low removal levels again likely indicate the complicated sensitivity of removal to the suite of system and solution variables.

5.1.7   Removal of Pesticides

These studies differ from others in that they involved smaller molecular weight organics and contaminants present in low ppb amounts. A clear effect of increased removal with amperage – yet a low amperage levels - was found. High removal levels were attained at these low amperage values.

5.1.8   Other Treatment Effects

Clearly EC treatment was effective in removing color.   The changes in ORP provided an interesting partial insight into the effect of EC treatment on solutions.   The low (negative) ORP values in the treated solutions indicate a strong reducing environment.   When the use of excessive power is avoided, the solution temperature increases were only slight and on the order of a few degrees. In the early runs where excessive power was used, total solids measurement provided a useful indication of the dissolution of blade material into the solution.   The reduction in TS with decreased power in the treated solutions provided allowed for a clear interpretation of this phenomenon. EC treatment resulted in an increase in pH in all runs except those where the feed solution was at a high pH (above 11).

5.1.9   Removal Levels with Position on the Periodic Chart

A qualitative correlation of removal results with position on the Periodic Chart may be possible. As shown in the next page, it appears that metals from the center of the chart were more consistently removed at high levels than elements towards the sides of the chart. For instance, Na has never been reported as being removed with iron or aluminum blades, Cs gave consistently low removals in the studies, as did Ba. Ca and Sr removals varied considerably in the runs made as did I and As. More in the center of the chart, Cr, Cd, Zn, Cu and Ag gave high removals in the runs made.   Possible exceptions to this correlation are Fe and Al which while not having any low removal levels, did have a range of removals.

5.1.10 Removal and Treatment Effects Summary

Considering all of the EC runs together, several treatment effects were indicated. These included:

- Overpowering - the use of excessive power increased temperature and the amount of floc but did not increase removal levels
- Threshold effect – low removals at low power for some contaminants

REMOVAL

Figure 5.1 Correlation of Removal Levels with Periodic Chart Position

- Amperage – when low amperage did not give significant removal, typically increased amperage helped
- 2nd pass – removal levels increased with running the EC treated solution through the system in a 2nd pass
- pH of feed – in several instances changing of pH had an effect on removal levels
- pH of treated solution – except for high pH feeds, pH increased with EC treatment
- salinity on removal – no direct effect was observed

- salinity on power – increased salinity and thus solution conductivity reduced the power necessary to provide amperage
- blade material – some differences in removal level were demonstrated
- antiscalant – a silica antiscalant was shown to inhibit the removal of calcium (but not silica)
- ORP – EC treatment decreased the ORP of solutions
- Temperature – temperature increased slightly with treatment and became considerable in cases of excessive power
- Matrix – the background or base solution (made up of common ions) did not appear to affect removal levels; however the presence of other contaminants (other species that could be removed at higher levels by EC treatment) did appear to affect removal in several of the runs.
- Removal of suspended solids – the highest removal at the lowest power were achieved with solution of suspended solids
- Removal of inorganics – removal of many inorganic elements was demonstrated
- Removal of organics – high removal of pesticides was demonstrated

5.2   DISCUSSION OF MEMBRANE TEST RESULTS

5.2.1   Fouling of UF Membrane

Various suspended solids solutions (oil-water emulsions, silt, humic and tannic acid) resulted in fouling of the UF membrane. Irreversible fouling occurred upon dipping the membrane in a test solution containing the suspended solids.   Additional irreversible fouling and reversible fouling occurred upon processing the suspended solid solutions through the membrane.

The fouling study results differed according to the nature of the suspended solid foulant. Those of an organic nature resulted in a higher level of irreversible fouling and less of a rebound in flux upon processing DI water after processing the test solution. Foulants containing more of an inorganic nature (silt) showed lower amounts of irreversible fouling, greater amounts of reversible fouling.

Of most importance, a suspended solid solution (oil-water emulsion) treated by EC resulted in a low fouling level similar to that of DI water.

5.2.2   Summary of Membrane Results

The studies demonstrated the degradation of UF membrane performance due to suspended solids including the irreversible fouling of the UF membranes. The studies also demonstrated that EC treatment lowered the fouling level of the oil-water emulsion solutions to that of DI water.

5.3   DISCUSSION OF ENERGY COST PROJECTIONS

The energy costs in Table 6 show relatively low costs for high levels of suspended solid removal. The costs were estimated based on an electrical cost of $0.08/kWh.   Power Water Systems' commercial EC units require 1/4th the power of the bench-scale unit used in the project. Thus the field energy costs corresponding to the removals of Table 6 should be considered to be a quarter those listed in the table.

Evident from Table 6 are estimated costs of less than $0.10/kgal ($0.26/m3) for removal of oil-water emulsions and silt from feed waters.

5.4   CONCLUSIONS

As in all research studies the results pertain only to the situations specifically studied.   The EC runs did not represent optimal run conditions – conditions that likely vary with each treatment situation.   Removal results differ in several instances with literature results – always in achieving lower removal levels than indicated in the literature. The most likely explanation for this is that suggested – the non-optimal processing done in the research studied.   In particular, the tests did not fully exercise the effects of pH, blade material, and amperage level for each contaminant solution studied.   To do so would have been prohibitive – both from a time (labor) and cost (analytical) standpoint.

What was achieved, however, was the successful meeting of the project objectives. First, this involved exploring the removal capabilities of the EC technology including its dependence on various system and solution variables.   The several possible concurrent reaction / removal mechanisms that may be operative (discussed in Chapter 2) complicate finding a simple explanation of results in terms of clear cause and effect. The test results demonstrate this very clearly in reflecting the breadth of effects and results that differ from contaminant to contaminant.

Second, the results do clearly indicate the most beneficial application of EC in terms of providing pretreatment to membrane systems.   The use of EC in front of a multi-membrane system of UF/RO or MF/RO has promise to improve performance of the membrane system and to broaden its application to include feedwater having high suspended solids levels.

The EC equipment is very simple as is its operation. This coupled with its high efficiency make it a strong candidate for pretreatment for both military and municipal membrane systems.

5.5   RECOMMENDATIONS

Field study of the EC process as pretreatment to a UF/RO or MF/RO system is indicated. This would serve to verify laboratory results on a continuously operating system, on real waters, and over an extended period of time.   Due to the extensive treatment capabilities of the EC system, field testing over a variety of conditions (waters) is recommended to fully explore the system capabilities.

More specifically, a field pilot unit consisting of EC / UF/ RO and of size large enough to utilize commercial equipment is recommended. The unit should be contained in a trailer to provide a self-contained portable system that could be used at a wide range of test locations and conditions. It is important that the system be reliable and capable of simple maintenance and support.

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